4—

LIGHT, PHOTOMETRY

AND

ILLUMINATING ENGINEERING

LIGHT, PHOTOMETRY
AND
ILLUMINATING ENGINEERING

Embodying a Thorough Revision of "Light, Photometry and Illumination"

BY

WILLIAM E. BARROWS

Professor of Electrical Engineering, University of Maine

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1925

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

This book has been designed as a text in illuminating engineering and a reference work for the practicing engineer. It is an outgrowth of the author's previous books, ELECTRICAL ILLUMINATING ENGINEERING and LIGHT, PHOTOMETRY AND ILLUMINATION. Approximately, two-thirds of the present text is new; specifically, Chapters X and XII to XIX are entirely new and Chapters IX and XI partly so.

In choosing this material, it has been the aim of the author to assemble the best ideas and thoughts available on the subject of artificial illumination and the choice of lighting equipment. In doing so the author has consulted freely the technical press, particularly the Transactions of the Illuminating Engineering Society and the Bulletins of the Edison Lamp Company and has drawn freely from the writings of illuminating engineers and experts who are authorities in their branches of the subject. The author wishes especially to acknowledge the excellent articles by H. E. Ives, M. Luckeish, E. B. Rosa, P. S. Millar, G. H. Stickney, A. L. Powell, Ward Harrison, A. S. Turner, A. B. Oday, H. E. Butler, J. H. Kurlander, A. E. Anderson, S. L. E. Rose, H. A. Smith, E. Parker, R. E. Harrington, R. W. Peden, W. H. Rademacher, J. R. Covelle, R. E. Greiner and H. Schroeder.

Much information on present practice will be found in the chapters on the different classes of lighting. These can be studied with reference to the fundamental principles taken up in the preceding chapters and form the basis for constructive criticism and progressive thought in the classroom. It will be noted that various types of lighting installations are discussed. It has been the aim to choose those types which illustrate certain classes of lighting and will assist the student in arriving at a rational solution of illuminating engineering problems.

W. E. Barrows.

University of Maine, Orono, Me.,
August, 1925.

CONTENTS

LIGHT, PHOTOMETRY, AND ILLUMINATING ENGINEERING

CHAPTER I

LIGHT AND ITS PHYSICAL PROPERTIES

The phenomenon of light is inherently the same as that of radiant heat, although the vibratory or wave motion is of different frequency. The light waves are those having a periodicity of such value that, when they are received by the retina of the eye, they produce the sensation of vision in the brain.

Since the velocity of light of all colors is the same, or 3×10^{11} mm. per second (186,000 miles per second), it follows that the wave length of the light in different parts of the spectrum varies inversely as the frequency of the corresponding wave. Thus, if the frequency of light producing highest sensibility is 5.5×10^{14} cycles per second, its wave length will be

$$\lambda = \frac{V}{f} = \frac{3 \times 10^{11}}{5.5 \times 10^{14}} = 545 \times 10^{-6} \text{ mm., or } 0.545\mu, \qquad (1)$$

where μ represents one-thousandth part of a millimeter. The eye responds to radiation between the limits of approximately 0.300 and 1.000μ, but the radiation easily visible to most eyes lies between 0.330μ in the violet end of the spectrum and 0.770μ in the red portion. Good visibility requires radiation between 0.410 and 0.760μ, or less than one octave. *Highest sensibility* occurs between 0.500 and 0.600μ. At frequencies lower or at wave lengths greater than those of red light the energy radiated is in the form of heat, and is known as the infra-red or ultra-red rays, also at wave lengths shorter than those of the violet light the radiation is again invisible and is known as the ultra-violet rays.

Frequency and Wave Length of Energy.—The following table is useful for comparing the frequencies and wave lengths of some of the common forms of energy of scientific interest.

TABLE 1

Frequency and Wave Length of Energy

Form of energy	Cycles per second	Wave-length in air
Alternating current field	15	12,500 miles
Alternating current field	25	7,500 miles
Alternating current field	60	3,100 miles
Alternating current field	125	1,500 miles
Wireless telegraph wave	10^5 to 10^7	10,000 to 100 ft.
Herzian waves	10^7 to 10^9	100 to 1 ft.
Infra-red rays	6×10^{11} to 4×10^{14}	0.2 to .00003 in.
Visible light	4×10^{14} to 7.7×10^{14}	.00003 to .000015 in.
Ultra-violet light	7.7×10^{14} to 3×10^{15}	.000015 to .000004 in.
Lowest audible sound wave	15	66 ft.
Highest audible sound wave	8,000	1.5 in.

Luminous radiation may be produced (1) by the influence of temperature, (2) by chemical action or electrical action, or (3) by a combination of temperature influence and chemical or electrical action. In most luminous sources luminosity is produced by solid bodies raised to high temperatures, the luminous radiation being due to the *incandescence* of the body. When light is produced by other means than by direct temperature, the interesting phenomena known as luminescence, fluorescence, and phosphorescence occur.

The phenomenon of *luminescence* is produced by chemical or electrical effects and nearly always occurs in gases. The luminosities of the so-called flame and luminous arcs and of the vapor lamps are examples of this phenomenon. With these sources the color of the light and the efficiency of the lamp become functions of the materials or gases involved rather than of the temperature.

Fluorescence refers to the property of a substance whereby some of the radiation which is absorbed by it is converted into radiation of a different wave length. It acts as a frequency converter and usually changes invisible radiation into radiation capable of exciting vision.

Phosphorescence is applied to that property of a body whereby it absorbs energy of radiation, such as light, in such a way as to

give it out again afterward, for example, as a glow, when placed in darkness.

Although a considerable amount of research work has been done in the investigation of fluorescence and phosphorescence, there is as yet little practical knowledge of these phenomena.

The type of phosphorescence illustrated by the firefly, with its luminous efficiency of about 90 per cent, has long been a fascinating subject for speculation and experiment. It is the production of so-called cold light by chemical reaction at low temperature. It has been determined that the firefly's phosphorescence is the result of an oxidation process, the elements of which have been isolated and named luciferin and luciferase. Similar heatless combustion has been obtained in laboratory experiments using potato juice and pyrogallic acid as the elements, but the resulting light was very feeble. Possibly further work may show how brighter light may be obtained, but it is altogether likely that the elements of this heatless combustion may be too costly to be economical. The firefly has the advantage that it can use the fuel over and over again, for in its system the products of combustion are reduced so that the original elements are renewed.

In considering now the subject of incandescence where luminosity is due entirely to temperature effects, it will be well to review the laws connecting radiation and temperature.

Black-body Radiation.—A body at any temperature other than absolute zero will radiate energy in all the wave lengths from zero upward; the wave length at which maximum radiation occurs depends on the temperature of the radiator. The amount of energy radiated varies according to certain laws which have been theoretically derived and experimentally verified. First, fundamentally, are the laws based on the principles laid down by Kirchhoff. Briefly these are:

1. At any given constant temperature every body radiates the same amount of energy that it receives.

2. Black radiation must exist in every completely enclosed cavity whose walls are opaque and of the same temperature.

Black radiation may be defined as the radiation from a black body, and a *black body* as one which is not transparent, does not reflect, but absorbs, all incident radiation at all temperatures. It is obvious that the total energy radiated from such a body is greater than that from any other dissimilar body at the same temperature.

Probably the most general law is that known as the *Stefan-Boltzmann law of radiation.* Briefly, this law is that the total radiation from a black body is proportional to the fourth power of its absolute temperature, or

$$W = kT^4 = k(t + 273)^4, \tag{2}$$

where T is the absolute temperature of the body; t the temperature in Centigrade degrees; and k the radiation constant = approximately 5.32×10^{-12}.

From the above equation, then, the net radiation of energy from a black body to the surrounding air would be

$$W = 5.32 \times 10^{-12}(T^4 - T_o^4) \text{ watts per square centimeter,} \tag{3}$$

where T_o is the absolute temperature of the surrounding air.

It will be seen that this law provides a means whereby a continuous *temperature scale* can be obtained from low to the very highest values of temperature, since, by transposing,

$$T = \sqrt[4]{T_o^4 + \frac{W}{(5.32 \times 10^{-12})}}, \tag{4}$$

where W is the radiation in watts per square centimeter, or

$$T = \sqrt[4]{T_o^4 + \frac{J}{(1.28 \times 10^{-12}}}, \tag{5}$$

if J is the radiation in calories per square centimeter per second.

Since the radiation of a body varies as the fourth power of its temperature, it is evident that the greatest efficiency of radiation

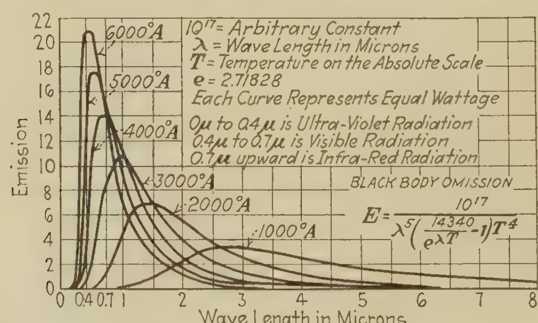


FIG. 1.—Black body radiation.

will be obtained at the highest temperatures. Although the amount of visible radiation from a luminous source is a small part of the total radiation, it follows from the above that the efficiency of a source as an illuminant will vary greatly with the temperature. The relative values of the radiation at different wave

lengths from black bodies at several temperatures are shown in Fig. 1. The total radiation is represented by the areas enclosed by the respective curves. Although the total area representing the radiation increases as the fourth power of the temperature in absolute degrees, it is evident that the rate of increase in visible radiation is still greater, due to the shifting of the maxima of the curves as indicated.

The Luminous Efficiency.—The relation of the visible radiation to the total radiation is an indication of the luminous efficiency of the source. This efficiency, therefore, increases with increase in temperature of the source, due to the shifting of the radiation curve toward the visible region. A maximum is reached at about 6000° absolute. At 5000° the maximum of the radiation curve is in the visible region and coincides with the maximum of the sensibility curve of the eye at about the middle of the visible spectrum.

Wien's "Displacement Law."[1]—Wien's investigations brought out his "*displacement law*" bearing on the shift of the maxima of the radiation curves. The substance of this law is that the product of the wave length, λ_m in microns, at which the energy radiation is a maximum, and the absolute temperature T, is equal to a constant a.

$$\lambda_m T = a = \text{constant}, \tag{6}$$

where a is equal to about 2,960 for a black body and 2,630 for platinum.

By combining this law with that of Stefan and Boltzmann, Wien deduced the relation for black bodies,

$$W_m T^{-5} = b = \text{constant}, \tag{7}$$

where W_m is the energy of radiation corresponding to the wave length λ_m of the maximum energy radiation, and T is the absolute temperature.

It was found that b was equal to about 14,600 for black bodies. For other than black bodies the law is complicated by the absorptive power of the body. For certain metals the relation is closely represented by the expression

$$W_m T^{-c} = \text{constant}, \tag{8}$$

while for other metals this equation will in no way hold. For polished platinum c is equal to about 6.0.

[1] *Trans. Illum. Eng. Soc.*, vol. 4, p. 67.

By applying these equations it can be shown that a temperature of 5000° absolute would be required for a black body and 4500° for a body resembling polished platinum in order to obtain the maximum of the energy curve near the center of the visible spectrum or at the wave length of about 0.545μ.

In the effort to secure high luminous efficiency by raising the temperature of the radiator, a limit, far below those mentioned above, is established by the impossibility of producing a substance capable of withstanding those high temperatures without disintegration. While the sun has been estimated to have a temperature of 6000° absolute, that of the positive crater of a carbon arc is believed to be between 3600 and 4200°; the incandescent gas mantle, 1900 to 2400°; osmium filament, 2250°; the tungsten filament of the 40-watt, type-B lamp, 2500°; of the 200-watt, type-C lamp, 2875°; and of the 900-watt, motion-picture lamp, 3300°. The melting point of tungsten is approximately 3670°, and of a carbon filament about 2050°. All these temperatures are expressed in Centigrade degrees measured from absolute zero.

Selective Radiation.—A higher luminous efficiency may be obtained for the same temperature, however, by employing a radiator capable of selective radiation in the short wave lengths. A black body is a "complete radiator," that is, it is said to radiate at any temperature a maximum amount of energy in every wave length. Such a body will be a complete absorber and will absorb all energy incident upon it. A body which is not a complete radiator will radiate less energy at each wave length than a black body at the same temperature. If the energy radiated in each wave length is reduced by a constant proportion, the ratio of the visible energy radiated to the total energy radiated will be the same as that of a black body, and the luminous efficiency will be the same as that of a black body at the same temperature. Such a body is termed a *gray body*, and, in place of absorbing all the energy falling upon it, it will reflect a constant percentage of each wave length. If a body radiates less energy than a black body at the same temperature, but radiates a relatively larger proportion of energy at certain wave lengths than at others compared with a black body, it may be said to *radiate selectively* in the former wave lengths. Thus, if a body radiates selectively in the wave lengths of the visible region its luminous efficiency will be greater than that of a black body at

the same temperature. This fact accounts in part for the higher efficiency of some of the new types of incandescent lamps, although the principal cause of the higher efficiency is the higher temperature at which they operate.

The relation of *visible to total radiation* of incandescent electric lamps is shown graphically by the energy curves derived by Drs.

FIG. 2.—Radiation curves for incandescent lamps.

Coblenz and Hyde[1] and shown in Fig. 2. These curves refer to lamps having filaments of untreated carbon (curve *a*), flashed carbon (curve *b*), tungsten (curve *c*), and osmium (curve *d*). The visible radiation is indicated by the shaded portion and extends from 0.4 to 0.7μ (thousandths of a millimeter). The

[1] *Bull. Bur. Stand.*, vol. 5, p. 339.

lamps were so operating that the amount of visible radiation was the same for each. It will be seen that the less invisible radiation from the metallic-filament lamps indicates a higher efficiency for these sources. It will also be seen that the maxima of the energy curves shift with these indications of increase in efficiency in the same direction as the maxima of the black-body radiation curves with increase of temperature. This is due in part to selective radiation, but largely to higher temperatures.

The ordinates of the shaded portion merely indicate the amount of radiant energy at those wave lengths and should not be mistaken for the visual effect of the radiation, which will be taken up in the following chapter.

From the preceding discussion it will be seen that the variation of luminous intensity with temperature follows definite laws within certain limits. The color of the light from an incandescent source becomes whiter as the temperature is increased. In luminescent sources there appears to be nothing definite in the relationship of intensity or color of the light to temperature. In some cases the intensity may decrease and the color change toward a blue or a violet hue, while in other cases, as in the mercury-vapor arc, there is an increase in intensity with an increase in temperature, and the spectrum broadens out, becoming more normal and containing more red rays.

It is in luminescent sources that the highest luminous efficiencies of industrial significance are obtainable. In the "flame" and "luminous" arc lamps the light is due to the luminescence of the vapor stream. Its intensity is not a function of the temperature, but depends upon the chemical nature of the substances fed into the arc. In the mercury-vapor arc and the Moore tube the color and the intensity of light are functions of the chemical composition of the gases which constitute the vapor stream and, while the intensity increases with increase in temperature, the variation is indefinite and in no way comparable with that of a black body.

Reflection, Absorption, and Transmission.—Rays of light falling upon a surface are either *reflected*, *absorbed*, or *transmitted* and perhaps refracted according to the nature of the substance of which the surface is composed.

Reflection.—The amount of light *reflected* from a particular surface depends upon (1) the molecular condition or color of the surface; (2) the angle of incidence, or the angle which the rays

make with a normal to the surface; and (3) the wave length or color of the incident rays. If the surface is smooth, the reflection is *specular* and the rays make an angle with a normal to the surface equal to the angle of incidence (Fig. 3*a*). If the surface is rough the reflected rays are *diffused* (Fig. 3*b*). By a proper choice and arrangement of the molecules of a substance, rays of a desired frequency may be reflected and all others absorbed, thus

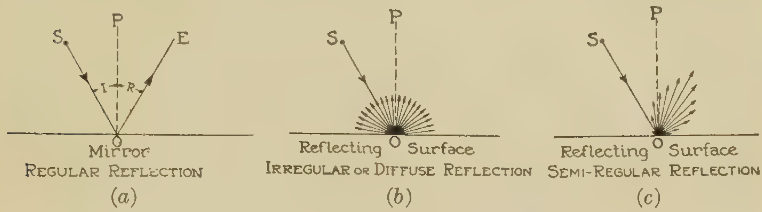


Fig. 3.—Regular and diffuse reflection.

giving rise to the color of the body. Substances differ greatly in their properties of absorption and reflection, and to these differences are due the variety of colors of objects. In general, the per cent of light reflected by different substances or surfaces is indicated in Table 2, representing the materials used for reflectors, for interior finishings, and in photometric work.

Effect of Varying the Angle of Incidence upon Reflection.—Investigations by Mr. Gilpin[1] show the effect upon the distribution of light of varying the incident angle, as well as the amount of

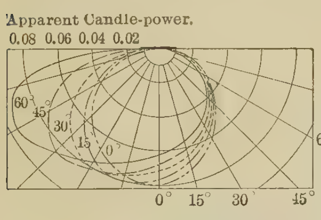


Fig. 4.—Pulp tint, white.

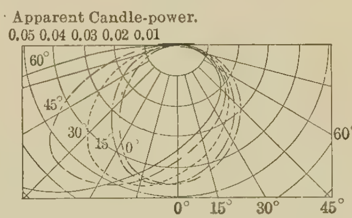


Fig. 5.—Silk fibre, orange-yellow.

light reflected for a number of wall papers. The efficiencies of different papers with different incident angles are given in Table 3. The mean values may be considered as corresponding to those values given in the table on following page. The distribution curves of reflected light from the samples of glossy and semigloss paper show a tendency toward specular reflection, while

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 854.

Table 2

Reflection Coefficients for Various Surfaces[1]

Material	Coefficient of reflection
Highly polished silver	.92
Mirrors silvered on the surface	.70–.85
Highly polished brass	.70–.75
Highly polished copper	.60–.70
Highly polished steel	.60
Speculum metal	.60–.80
Polished gold	.50–.55
Burnished copper	.40–.50
White blotting paper	.82
White cartridge paper	.80
Ordinary foolscap	.70
Chrome yellow paper	.62
Orange paper	.50
Plain deal (clean)	.45
Yellow wall paper	.40
Yellow painted wall	.40
Light pink paper	.36
Yellow cardboard	.30
Light blue cardboard	.25
Brown cardboard	.20
Plain deal (dirty)	.20
Yellow painted wall (dirty)	.20
Emerald green paper	.18
Dark brown paper	.13
Vermilion paper	.12
Blue-green paper	.12
Cobalt blue paper	.12
Black paper	.05
Deep chocolate paper	.04
French ultra-marine blue paper	.035
Black cloth	.012
Black velvet	.004
Additions by the author:	
Tracing cloth	.30
Macadam road	.12
Dead black paint	.01

[1] Dr. Bell, "The Art of Illumination," pp. 47 and 52, 1902.

the reflection from the matt and rough samples shows the result of the diffusing properties of the surfaces.

Figures 4, 5, 6 and 7 show the curves representing the distribution of light in a normal plane from small illuminated surfaces composed of some of the samples included in the table, with the

incident light rays making different angles with the normal. These figures refer to samples 1, 4, 19, and 21, respectively, as stated in the legends. These represent, in general, the performance of the different classes of paper and will be found useful in designing installations for interior illumination and in determining the height and the location of lamps when these or similar materials are used on the walls or ceilings.

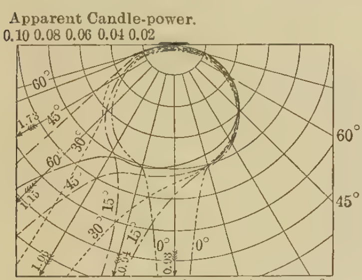


Fig. 6.—Varnished tile, cream.

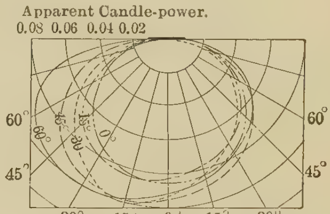


Fig. 7.—White blotting paper.

TABLE 3

Effect of Varying the Incident Angle upon Reflection

Kind of paper	Finish	Color	Efficiency for incident angle with normal of 60°	45°	30°	15°	0°	Mean
Pulp tint..........	Matt (smooth)...	White..........	56.0	61.5	58.2	56.5	54.6	57.3
Pulp tint..........	Matt (smooth)...	Light buff.......	46.0	47.4	45.7	43.8	42.7	45.1
Pulp tint..........	Matt (smooth)...	Lt. orange yel...	42.5	44.1	43.0	42.5	42.4	42.9
Silk fiber..........	Semi-gloss.......	Orange yellow...	38.5	36.0	33.3	31.4	30.0	33.8
Silk fiber..........	Semi-gloss.......	French gray.....	37.6	32.2	25.6	22.6	21.0	26.0
Silk fiber..........	Semi-gloss.......	Lt. pea green....	27.8	25.7	21.4	18.9	18.5	22.2
Silk fiber..........	Semi-gloss.......	Dk. pea green....	23.5	18.6	14.4	11.2	9.3	15.4
Silk fiber..........	Semi-gloss.......	Light brown.....	16.8	14.6	11.7	10.9	10.3	12.9
Silk fiber..........	Semi-gloss.......	Light blue.......	15.5	13.0	10.0	9.2	8.1	11.2
Silk fiber..........	Semi-gloss.......	Cherry red......	13.7	11.8	8.9	7.0	6.3	9.5
Imported stock....	Fibrous.........	Tan............	19.3	19.0	17.3	16.3	15.7	17.5
Imported stock....	Fibrous.........	Light blue.......	13.5	13.4	12.0	11.0	10.2	12.0
Duplex...........	Rough..........	Light blue.......	12.7	12.0	10.5	9.1	8.2	10.5
Duplex...........	Rough..........	Cherry..........	6.6	6.4	6.2	6.0	5.7	6.2
Plain.............	Rough..........	Yellow buff......	31.4	34.3	35.6	35.6	35.0	34.4
Plain.............	Rough..........	Lt. pea green....	21.5	20.4	19.8	18.8	18.2	19.7
Plain.............	Rough..........	Dk. pea green....	13.4	12.7	11.3	10.7	8.9	11.6
Plain.............	Rough..........	Deep red........	7.3	7.0	5.9	5.3	4.9	6.1
Varnished tile.....	Glossy..........	Cream..	66.3	71.1	73.1	71.8	70.8	70.6
Imported.........	Embossed gloss..	Gilt............	54.0	49.3	43.7	37.7	27.0	41.7
White blotter......	....	....	72.7	80.0	73.9	72.9	71.1	74.0

Transmission and Absorption.—It is obvious that the amount of light transmitted by a translucent medium depends upon the quality of the medium and the color of the light transmitted and is equal to the difference between the amount of light received and the amount reflected or absorbed. The principal concern here is with the transmission, or absorption, of the atmosphere and with the different translucent mediums used for illuminating purposes. Daylight illumination is derived exclusively from the sun, and sunlight is greatly modified by the atmosphere. A varying proportion of the sun's rays reach the earth's surface after selective reflection and absorption from minute particles in the atmosphere, from cloud masses, and from the surface of the earth. The changes which occur in sunlight in its transmission through the atmosphere are indicated by the averages of 6 months' observations (February to August, 1903), given in Table 4,[1] which gives the average per cent, transmitted by the atmosphere, of light of the different wave lengths, with the sun in zenith.

Table 4

Absorption by the Atmosphere

Wave-length in microns	Percentage transmitted
.40	47.5
.45	55.3
.50	62.4
.60	68.2
.70	75.6
.80	80.1

It will be seen that the red end of the sun's spectrum is reduced about 20 per cent by the influence of the atmosphere, while the violet end loses more than half of its initial intensity.

Of the indirect components of daylight, the light from the cloudless sky is relatively richer in blue and violet and weaker in red rays than is sunlight by greatly varying amounts, which depend upon the state of the atmosphere. Daylight composed of the direct rays from the sun and the indirect rays from the sky will differ but little, however, from sunlight, since sunlight is by far the dominant factor. Skylight, on the other hand, will be much bluer, since the direct rays of the sun are intercepted.

The increase in absorption of the sun's rays by the atmosphere as the sun passes from the zenith is considerable, as is shown by

[1] *Astrophys. Jour.*, vol. 19, p. 313.

the difference in the intensity both of heat and of light when the sun is high in the sky and when it is near the horizon. It is also represented by the decrease in intensity both of light and of heat from summer to winter.

The amount of *light absorbed by the globes* and glassware used with lamps to prolong the life of the filament or of the electrode, to diffuse the light and lower the intrinsic brightness of the source, or to transmit light of a desired color will be seen from Table 5 to vary from 5 to 95 per cent:

Table 5

Absorption of Glassware

Glassware	Absorption per cent	Efficiency per cent
Clear glass	5–12	88–95
Light sand blast	10–20	80–90
Alabaster	10–20	80–90
Canary colored	15–20	80–85
Light blue alabaster	15–25	75–85
Heavy blue alabaster	20–30	70–80
Ribbed glass	15–30	70–85
Opaline glass	15–40	60–85
Ground glass	20–30	70–80
Medium opalescent	25–40	60–75
Heavy opalescent	30–60	40–70
Flame glass	30–60	40–70
Signal green	80–90	10–20
Ruby glass	85–90	10–15
Cobalt blue	90–95	5–10

The variations in the values above are, obviously, due to the difference in the thickness and the density of the glass.

It is obvious that the percentage of light absorbed by an opaque surface is equal to 100 minus the per cent reflected. The amount transmitted by a translucent material is equal to the total incident light less that reflected and that absorbed in transmission.

Refraction.—Refraction is the change in the direction of light rays when they pass from one transparent medium to another of different density. This change is illustrated in Fig. 8, when light from a source S strikes the surface of a piece of glass having

smooth, parallel sides. The rays are refracted upon entering the glass and again, in the reverse order, upon leaving the glass. If the two surfaces of the glass were not parallel, the direction of the transmitted rays would be modified accordingly.

If the eye be placed at E, the light would appear to come from S' instead of S. The manufacture of lenses is based on this principle of refraction, as will be explained in Chap. XVIII.

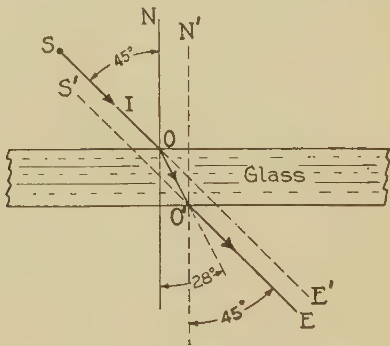


Fig. 8.—The principle of refraction.

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is termed the *index of refraction,* which, in Fig. 8, is

$$\frac{\sin 45 \text{ deg.}}{\sin 28 \text{ deg.}} = \frac{0.707}{0.470} = 1.51.$$

Different substances have different indices of refraction. A few of the most important are given in Table 6.

Table 6

Water	1.33	Glass, crown	1.51 to 1.54
Sea water	1.34	Glass, flint	1.56 to 1.78
Alcohol	1.37	Diamond	2.47 to 2.75
Carbon disulphide	1.68	Air	1.00029
Canada balsam	1.54		

The Intensity of Natural Illumination.—The values of the natural-incident illumination of the earth vary from approximately zero for a dark moonless night with the sky heavily overcast to something like 13,000 foot-candles for the normal intensity and 10,000 foot-candles for the horizontal illumination due to direct rays from a noonday sun with the sky clear.

With a full moon, the maximum normal and horizontal intensities during the night, in a case studied, were 0.0388 and 0.0216

foot-candle, respectively. The rate of increase during the hour preceding sunrise is surprising. The intensity at about 7 min. before sunrise was approximately 10,000 times that at 1 hr. previous. At about 25 min. before sunrise and 25 min. after sunset the illumination was approximately 2 foot-candles. It was also found that certain cloud formations have the effect of

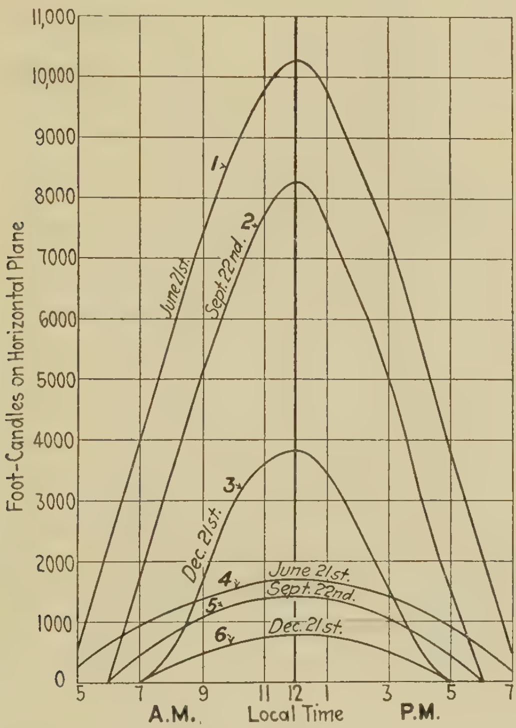


FIG. 9.—Diurnal variation in daylight illumination. Cloudless sky. Latitude 42° North. Curves 1, 2 and 3 represent illumination due to both sun and sky. Curves 4, 5, and 6 refer to illumination from a clear sky only.

increasing the intensity of illumination by diffusion, while other clouds act as absorbing media and reduce the illumination intensity. Variations in illumination intensity due to clouds are often of a large order and sometimes occur suddenly, but in the absence of clouds the rate of change of intensity between an hour after sunrise and an hour before sunset is regular. During the hours of dawn and twilight the rate of change of intensity is very high.

In Fig. 9 are curves showing the variation of natural illumination through the day for three periods of the year. The latitude is approximately that of Chicago or Boston—42° N. Curves 1, 2, and 3 refer to the horizontal illumination from both sun and sky on a clear day, while curves 4, 5, and 6 refer to the illumina-

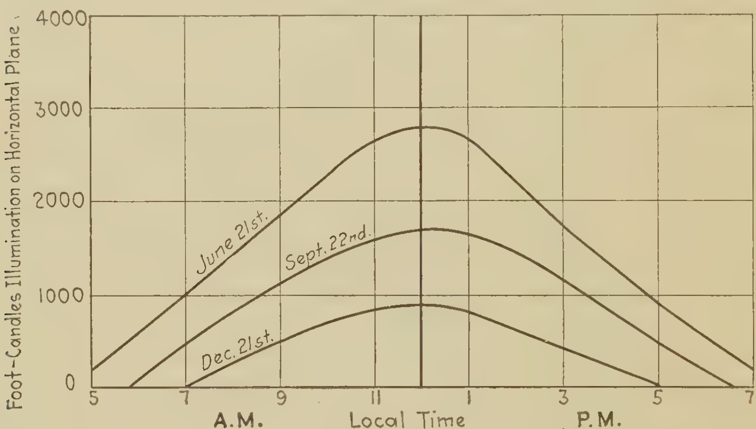


FIG. 10.—Diurnal variation in daylight illumination. Cloudy sky. Latitude 42° North. Sky so densely clouded that position of sun could not be seen.

tion from a clear, blue sky only. It will be noted that these data are for the longest, shortest, and average days of the year.

In Fig. 10 are shown curves for the same dates as above, based on a sky so densely clouded that the position of the sun could not be determined. The average sky, with thin clouds or haze, or scattered white clouds, produces about twice this illumination.

CHAPTER II

THE LUMINOUS EQUIVALENT OF RADIATION

A definition of light in terms of its physiological influence is as yet more or less arbitrary, and depends primarily upon the conception of the luminous equivalent of radiation. The problem is to determine the quantity and quality of light from a physiological basis, having given a certain spectral distribution of radiant energy. The luminous equivalent of radiation varies greatly with the wave length and to some extent with the intensity of the radiation concerned. It is a complex function of quality, quantity, and duration. It may be considered with reference to the *subjective sensation produced* or to the *objective stimulus causing*, or capable of causing, the sensation. The principle of the conservation of energy cannot be applied to light in either a subjective or an objective sense.

The problems of illuminating engineering have insistently demanded the establishment of some definite relation between light and its luminous equivalent. While no complete and precise solution of the subject has yet been developed, certain essential interrelations between functions which will form the basis of such a solution have been established and will now be considered. These may include:

1. The spectral distribution of radiant energy from different sources of light.
2. The sensibility and the visibility of the eye to radiation from different regions of the spectrum.
3. The sensibility and the visibility of the eye to intensity and variations in intensity of light.

Spectral Curves for Luminous Sources.—The spectral distributions of energy from some of the artificial sources of light have been shown in the preceding chapter. Other curves bearing more particularly on the distribution of energy in the visible region were determined by Dr. Ives[1] and are reproduced in Fig. 11.

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 204.

These results are qualitative rather than quantitative and are plotted to cross at 0.59μ. These curves represent merely the distribution of the radiation in the spectral region and, while they represent to a considerable extent the color values of the light, they give no clue as to the physiological effect upon the eye.

In order to express *light in terms of radiation*, the visibility of the human eye for the same amount of radiant energy at each wave length of the visible spectrum, and the variation of sensibility with intensity at constant wave length, must be known. Then spectral energy multiplied by the relative sensibility at each

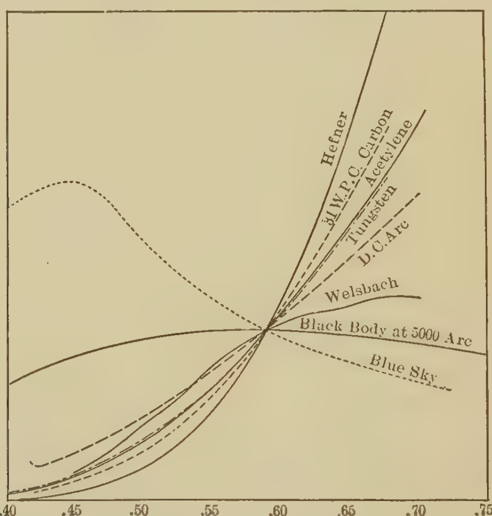


Fig. 11.—Spectral curves for luminous sources.

wave length is luminosity or objective light and the effect of this objective light upon the eye with respect to its variation of sensibility with intensity will give the subjective light or visual sensation.

The Luminosity of Monochromatic Light.—The relative visual sensibility of the eye to light from different parts of the spectrum, or the luminosity of monochromatic light, as investigated by Dr. Ives, is shown in Fig. 12. This curve shows the luminosity of different wave-length light reduced to a normal uniform energy spectrum. While the curves in the preceding chapter show that a small part of the total radiation is in the visible region, this curve shows that much of the visible radiation is of low effective value. In this figure it will be seen that, for a con-

stant energy distribution in the spectrum, maximum luminosity occurs at 0.555μ.

Knowing the relative luminosity for the same amount of energy in different parts of the spectrum and the spectral energy curves for the various illuminants, one can easily obtain the luminosity curves for the different illuminants by multiplying the value of the energy at the various wave lengths by the relative luminosity of the energy of the respective wave lengths. Such curves will show the relative intensities of sensation produced by different parts of the spectrum for the particular

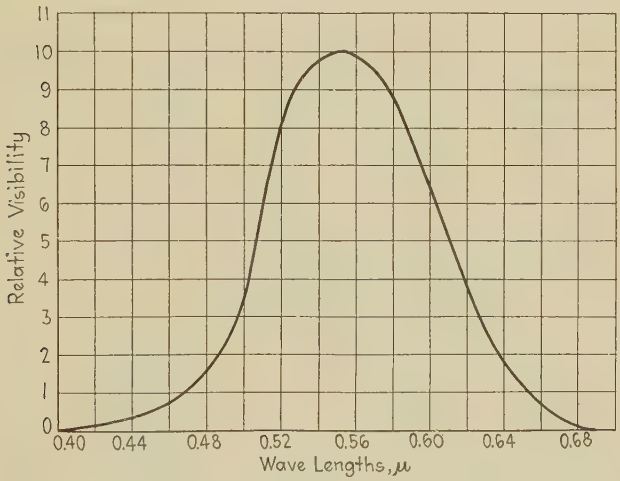


FIG. 12.—Spectral luminosity-curve of the average eye for a source of uniform energy-intensity.

illuminant. While maximum sensibility occurs at 0.555μ with uniform energy distribution in the spectrum, the wave length of maximum luminosity for most of the artificial sources of light shifts toward the red end of the spectrum, due to the predominance of energy of the red wave lengths.

Such curves are shown in Fig. 13. *A* shows the luminosity curve of a normal uniform energy spectrum, *B* the energy-distribution curve of an actual source, and *C* the luminosity curve corresponding to the energy distribution in *B*. The luminosity curves for different types of illuminants will differ in shape somewhat, due to the difference in the distribution of energy in the spectrum.

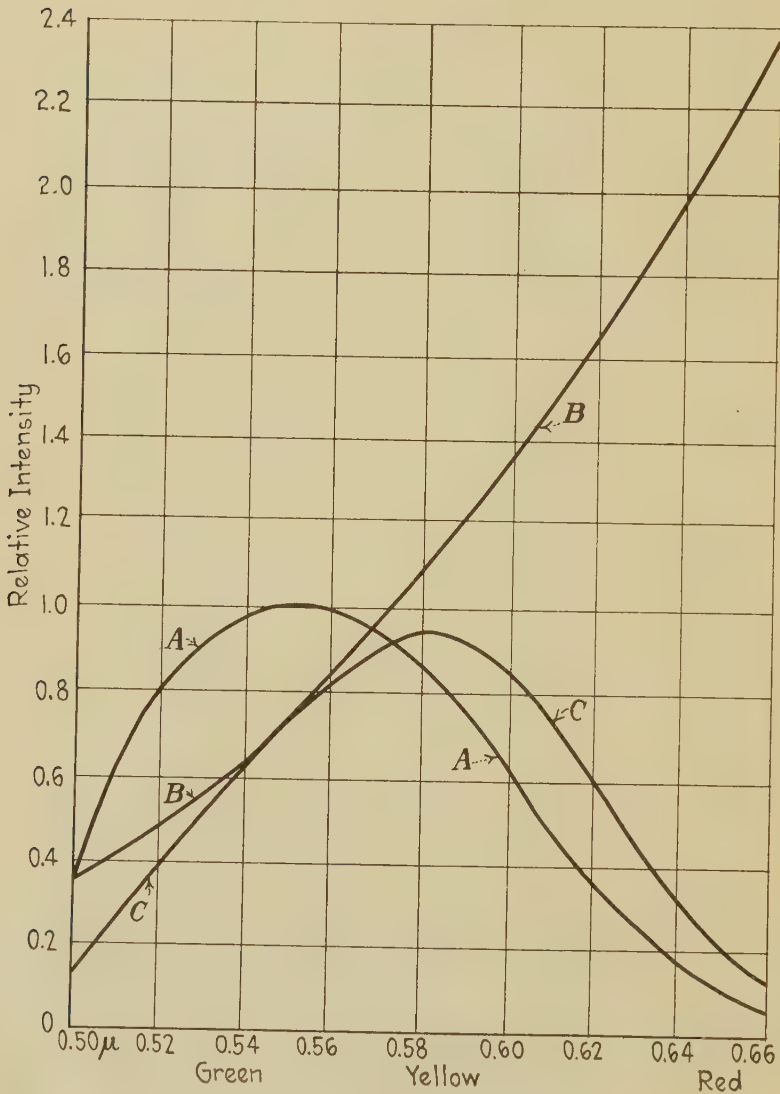


FIG. 13.—Luminosity curve for an incandescent lamp.

A Luminosity-curve for a source of uniform energy-intensity.
B Energy-distribution curve of an actual source.
C Luminosity-curve corresponding to the energy distribution in B.

The Reduced Luminous Efficiency.—That the amount of visible radiation from luminous sources is a small part of the total radiation may be inferred from the curves of Fig. 2 and is verified by the results obtained by various investigators in efforts to determine the mechanical equivalent of light. These results from different sources, although differing in many instances by several hundred per cent for the same illuminant, all indicate a low percentage of visible radiation.

Results of this nature derived by Dr. Ives,[1] giving what is termed the "reduced luminous efficiency," are shown in Table 7. This table gives data for some of the commercial illuminants in terms of a theoretically ideal source, that is, one which radiates its entire energy in the most efficient region of the visible spectrum. Since there is a direct relation between the amount of light flux emitted by an illuminant and the reduced luminous efficiency, one may easily obtain the relative equivalent for any other light source from the ratio of the lumens per watt for the lamps in question.

TABLE 7

The Reduced Luminous Efficiency of Light Sources

Source	Spherical candles per watt applied	Lumens per watt applied	Reduced luminous efficiency, per cent
Ideal yellow-green source, wave length 0.555μ	65	800	100
Firefly	?	?	96.5
Black body at 6000°	10	125	15
Black body at 6000° between 0.400 and 0.700μ	26	330	40
Carbon lamp, 4 watt	0.21	2.6	0.31
Tungsten lamp	0.63	7.9	0.95
Direct-current arc lamp	1.1	13.8	1.66
Gas-filled Mazda lamp	1.6	16	2
Yellow-flame arc lamp	3.0	37.8	4.54
Quartz mercury-vapor lamp	3.4	42.8	5.15

Visual sensibility to variations in intensity decreases continually with increasing intensity. Compared with other physical instruments, the eye has a most extraordinary range. It may be used with ease at intensities a million times the minimum perceptible intensity. This great power of accommodation is due chiefly to the decrease of sensibility with increase in intensity.

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 113; *Elec. World*, vol. 57, p. 1565.

The part which the eye plays in protecting itself against high intensities and adapting itself to low intensities can be best understood from a brief description of its construction.

The Human Eye.—The eye consists essentially of three parts—the *iris*, the *focusing lens*, and the *retina* (see Fig. 14). It resembles a camera in general structure and action. The *iris* is a diaphragm, which expands or contracts to regulate, to a certain extent, the amount of light which, passing through the focusing lens, falls upon the retina at the rear of the eyeball. The *focusing* (crystalline) *lens*, under the control of the ciliary

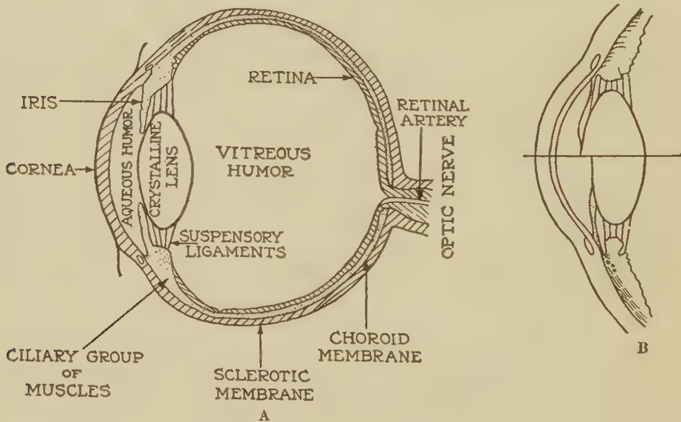


Fig. 14.—Cross section of the human eye.

muscles, is regulated so as to focus the images exactly upon the retina. The *retina* contains the optical nerves, which communicate with the brain. At the center of the retina is the region of greatest sensitiveness, known as the "fovea." It is at this spot that vision is most acute and where the image is formed when the eye is directed at the object of vision. The impression formed on the remainder of the retina is used merely for orientation.

The peculiarities of the optical system with reference to different intensities of light have given rise to the theory of a double nerve system in the retina. These nerves are known as the "rods" and "cones" and have decidedly different sensibilities in respect both to intensity of light and to color of stimuli.

The *cones* are supposed to be the form-receiving and color-perceiving elements of the retina; in other words, they are the visual cells.

The supposition is that the *rods* form the special apparatus for vision in dim light (night vision). They contain a pigment, known as visual purple, which is very sensitive to light. This visual purple is found only in the external segments of the rods; the cones do not contain it; therefore the fovea, which has only cones, does not contain it. It has been shown that a photograph may be made upon the surface of the retina by the bleaching of the visual purple where it is exposed to light. In the visual purple there is, therefore, an unstable substance readily decomposed by the mechanical or chemical effect of the ether waves. Some radiations are very much more active than others in bleaching this substance, greenish-yellow being most active, yellow next, blue next, violet next, and red least active in this process.

It has been shown that provision has been made in the retina for the constant regeneration of the visual purple, the restoration process taking place rapidly in dim light or darkness. The external segments of the rods impinge upon a layer of heavily pigmented cells—the pigmentary layer mentioned above. When the eye is exposed to light, the black pigment of these cells migrates so as to be in position to restore the color to the bleached or used-up visual purple. Additional experiments on this subject have shown that the velocity of the bleaching of visual purple by light under comparable conditions of concentration, volume, and surface exposed is directly proportional to the intensity. The experiments also confirmed the Bunsen-Roscoe law, which states that, in order to produce a definite photochemical change in a given system, the product of the light intensity and the time of its action must be a constant. At low intensities, below 0.02 foot-candle, vision appears to be accomplished by the retinal rods alone, while vision at higher intensities brings into play the less sensitive but more efficient retinal cones. The two functions overlap widely, so that the transition from rod to cone vision is very gradual.

At intensities greater than 1 foot-candle the cones exert the predominating influence and show maximum sensibility to light of a yellowish-green hue, while at low intensities, where the rods only respond, the eye is most sensitive to light from the bluish-green part of the spectrum. Thus the eye accommodates itself to high or low intensities by closing or opening the iris and by employing sets of nerves of different sensibilities.

The human eye is not achromatic and is not corrected for chromatic aberration. Its dispersive power is slightly greater than that of water. It is known that for near vision the normal eye will generally focus itself for blue rays, while difficulty is experienced in attempting to focus the eye for red rays. The reverse is true for distant vision. While this is true for large and small distances of vision, differences in the ease of accommodation for red and blue rays become less marked for vision at intermediate distances. At a distance of 1 m., according to M. Luckiesh,[1] no noticeable difference in ease of accommodation for red and blue rays appeared to three observers who had experienced no abnormality in their power of accommodation.

As a person increases in age, the elasticity of the lens diminishes, thus reducing the accommodation of the eye. This change begins at an early age and continues through life. According to Godinez,[2] the amplitude of accommodation at different ages is as indicated in the following table:

TABLE 8

Accommodation of the Eye

Age in years	Amplitude of accommodation diopters
10	14
15	12
20	10
30	7
40	4.5
50	2.5
60	1.0
75	0.0

Experimental data obtained by Cravath[3] show that the intensity of illumination required by individuals of different ages for good visibility is, in general, proportionally identified with the age of the individual, as might be inferred from the above table.

The unconsciousness of the great variations in the amount of natural light by which people see and the absence of annoyance or discomfort under even extreme cases merely corroborate the great range of adaptability and accommodation of the human eye.

Glare.—Glare may be defined as any brightness within the field of vision of such a character as to cause discomfort, annoyance,

[1] *Elec. World*, vol. 58, p. 1255.

[2] *Trans. Illum. Eng. Soc.*, vol. 6, p. 802.

[3] *Trans. Illum. Eng. Soc.*, vol. 6, p. 793.

interference with vision, or eye fatigue. It is one of the most common and serious faults of lighting installations.

Glare is objectionable because, when continued, it tends to injure the eye and to disturb the nervous system; it causes discomfort and fatigue, and thus reduces the efficiency of the individual; it interferes with clear vision, and thus reduces the efficiency and, in many cases, increases the risk of accident or injury to the worker.

There are five principal causes of glare:

1. The light source may be too bright.
2. The light source may be of too great candle power in the direction of the eye.
3. A given light source may be located at too short a distance from the eye, or it may lie too near the center of the field of vision, for comfort.
4. The contrast between the light source and its darker surroundings may be too great.
5. The time of exposure may be too great, that is, the eye may be subjected to the strain caused by a light source of given strength within the field of vision for too long a time.

The maximum intensity of light in the direct range of vision which the eye can endure without annoyance and possible harm is about 4 or 5 candles per square inch. The greater the brightness or the larger the area of the source the more will the eye be affected. Only paraffin candles, oil lamps, and certain gas and kerosene lamps give a flame of intensity below this limit. Other sources of light having an intrinsic brightness above this value should be surrounded with a globe of diffusing material of such size and diffractiveness as to present an intensity not greater than 4 or 5 candles per square inch.

Luminous sources should be so placed that the rays will not pass directly into the eye. The result of sources thus wrongly located is that objects back of the source, with direct rays, and the reflecting medium, if the rays are reflected, are more or less indistinct. Light coming from an unusual angle should be avoided. Light is usually received from above and the retina becomes accustomed to light from that direction. Light reflected into the eye from below, as from snow, or the direct rays, as from footlights, may not only cause fatigue but sometimes temporary blindness. *Streaks of light* and *sharp contrasts* are injurious to the eye, the effect being similar to that of a flickering light.

During all work with *ultra-violet rays* it is necessary to protect the eyes with suitable glasses, since it has been found that exposure of the unprotected eye to light of short wave lengths extending far into the ultra-violet produces very serious and often lasting injuries to this organ.

Brightness of Light Sources.—The intensities of some of the common sources of light in candle power per square inch are given in the following table, composed of data compiled from various sources, chiefly from results by Dr. Ives and Mr. Luckiesh.[1]

Table 9

Brightness of Light Sources

Source	Candle-power per square inch
The Moore tube	0.6
Dark overcast sky	1.0
Blue sky	2.2
Overcast sky	3.3
Frosted incandescent lamp (25 watt tungsten) — Tip	1.67
Frosted incandescent lamp (25 watt tungsten) — Side	6
Candle flame	2-4
Gas flame (fish tail)	2.7
Oil lamp	3–5
Cement pavement illuminated by sunlight	6
Kerosene lamp	9
Cumulus sky	10.4
Cooper-Hewitt lamp	14.9–16.7
Welsbach gas mantle	20–35
Welsbach mesh	53
Acetylene flame 1/4 ft. burner	33
Acetylene flame 1 ft. burner	53
Enclosed a. c. arc (depending on globe)	75–200
Enclosed d. c. arc (depending on globe)	100–500
Incandescent lamp (4 watts per candle)	325
Incandescent lamp (3.5 watts per candle)	400
Incandescent lamp 3.1 watts per candle)	485
Tantalum lamp (2 watts per candle)	580
Gem lamp (2.5 watts per candle)	750
Tungsten filament (1.25 watts per candle)	1060
Sun on the horizon	2000
Nernst glower (115 volts, 6 amps. d. c.)	3010
Magnetite arc	4000
Flaming arc	5000
Open arc lamp	10,000–50,000
Open arc crater	84,000
Sun 30 degrees above the horizon	500,000
Sun at zenith	600,000

[1] *Elec. World*, vol. 57, p. 438; *Trans. Illum. Eng. Soc.*, vol. 6, p. 687.

While the spectrum of all illuminants extends into the region of the ultra-violet rays, the harmful effect of the ultra-violet radiation is made negligible, due to the absorption of these rays by the enclosing glassware usually employed. When quartz glass is used as the medium for enclosing the luminous sources, as in high-temperature vapor lamps, an auxiliary globe of ordinary glass should be used, since quartz glass is translucent to the ultra-violet radiation. None of the existing artificial illuminants thus enclosed with ordinary glass radiate ultra-violet rays of a value near so great as the amount of similar radiation from the sun for the same intensity of illumination.

Experience shows that at 1 *or* 2 *foot-candles* the eye is working so near its normal condition that any further increase in illumination is of relatively small value. The values here specified are those affecting the eye and not those by which the objects are illuminated. This must necessarily be reflected light and, as the coefficients of reflection and diffusion vary over a wide range, the calculation of the amount of light required from the primary source is not a simple problem. However, if the class of service for which artificial light is to be used be known, the approximate intensity of the source of light required can be calculated from general physiological and physical data. The lowest permissible illumination is, of course, for work on light-colored objects, or where only the general outlines of the objects are required, while the highest illumination would be used for close discrimination of details on dark objects.

The subject of light and its physiological effect thus far has been considered in a general sense. A deeper study of it involves a distinction between terms often used indiscriminately. Moreover, with an understanding of the general features of the subject and of the construction and operation of the eye it is possible more easily to understand the essentials tending toward the establishment of a light scale for the average human eye in terms of radiation.

In the following discussion distinction is made between sensation, sensibility, and visibility, as well as between radiation, illumination, luminosity, and visual brightness.

Sensation is the subjective effect produced by light, while *visibility* refers in the objective sense to the acuteness of vision or the ability to distinguish detail. *Sensibility* may refer to the sensitiveness of the eye to changes in either subjective or objective light.

By means of visible radiation an object is illuminated, objective light, and the illumination is proportional to the radiation. *Luminosity* is the subjective equivalent of objective illumination. *Visual brightness* is the sensation produced by the illumination and is a logarithmic function of the luminosity.

Fechner's Law.—About 1830, Weber observed that the least perceptible increment to a stimulus affecting several of the sense organs, including the organs of vision, under fixed conditions of fatigue, attention, and expectation, bore a definite relation to the amount of that stimulus. Fechner later extended these investigations and formulated his results in the mathematical expression

$$\frac{dI}{I} = \text{constant}, \tag{9}$$

where I is the value of the stimulus and dI the least perceptible increment.

This law appears to hold over a wide range of intensities, failing only at very low and exceedingly high values. Fechner proceeded further to assume that the above constant was proportional to the corresponding increment to the sensation or physiological conception of light, and derived the expression

$$B = c\left(\log \frac{I}{I_o}\right), \tag{10}$$

where I is the intensity as above, and I_o is the threshold value or the least perceptible value of intensity, and c is a proportionality constant.

The values of I_o are given in Table 10.

Table 10

Least Perceptible Illumination

Wave-lengths	.430	.470	.505	.535	.575	.605	.670μ
Color of light	violet	blue	green	greenish-yellow	yellow	orange	red
Least perceptible illumination (I_o.)	.00012	.00012	.00017	.00072	.0029	.0056	.06

Although these expressions have been extended[1] to apply to all values of stimuli and are rather lengthy, the fact remains that for ordinary intensities Fechner's equations will give very approximate results. The result of expressing Fechner's equations in words is sometimes termed "*Fechner's law of sensation,*"

[1] *Bull. Bur. Stand.*, vol. 5, p. 291.

which, briefly stated, is this: The same percentage change in intensity of illumination, calculated from the least amount perceptible to the eye, gives the same change in sensation. In other words, the sensations produced by the optical nerves vary approximately as the logarithm of the value of the stimuli producing those sensations. This law, for light of the color of that from the most common illuminants, is represented graphically by the curve in Fig. 15 plotted with intensities in foot-candles as abscissæ and the values of the logarithms of intensities as ordinates. Referring to this curve, it will be seen that the same percentage change in intensity produces the same change in

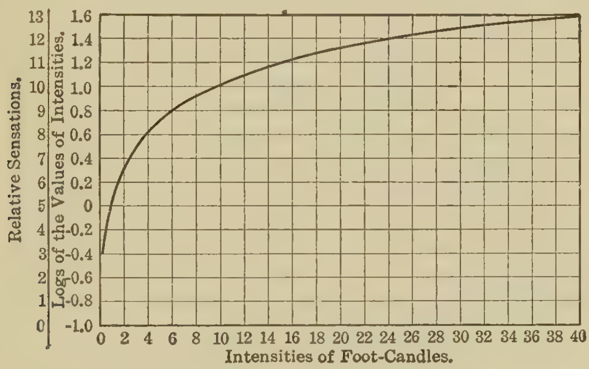


FIG. 15.—Relative sensations of brightness for different illumination intensities.

sensation. Thus, by increasing the intensity from 2 to 4 foot-candles the same change in sensation will be obtained as if the intensity were increased from 4 to 8 or from 20 to 40 foot-candles, the percentage increase being the same in all cases.

A study of this law will reveal the reason for the statement often seen in the technical press, that the effects produced by the use of additional lamps do not warrant the additional expenditure of energy. This law is, therefore, of much practical importance and should be understood by every man who pretends to handle illumination problems with engineering intelligence. It might be stated that this law fails to hold at illumination intensities of exceedingly high or low values, but since these values are far removed from those used in practice the fact becomes of little consequence.

The visual sensibility of the eye to the same amount of radiation of various wave lengths varies considerably with variations

in the intensity of radiation. The region of maximum sensibility shifts with increasing intensity from the bluish-green over to the yellowish-green.[1] This is shown by the curves of Fig. 16. These curves show the sensibility of the eye as a function of the wave length of light with a uniform distribution of energy in the spectrum. It will be seen that, with increasing intensity, the visibility curve broadens and the region of maximum visibility shifts toward the red end of the spectrum. An understanding of this variation of the visibility of radiation is of the utmost importance. It shows that the assumption of luminosity proportional to intensity can be true only under special conditions and with certain limitations. Fortunately, the greatest variations do not occur

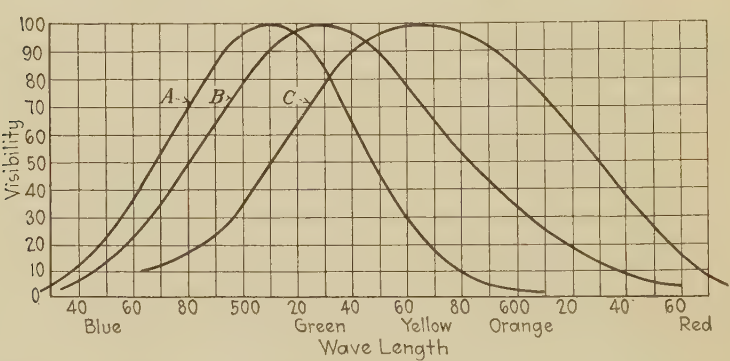


FIG. 16.—Variation of visual sensation with wave length or color of incident light. Curve A, low intensity. Curve B, high average intensity. Curve C, very high intensity.

within the range of illumination intensities most common in practice.

Visual Acuity and Wave Length of Light.—The ability of the eye to distinguish detail depends largely upon the character of the light which enters the eye, according to Luckiesh.[2]

This is attributed to the fact that the eye is not achromatic. It has been shown by Bell[3] and Luckiesh[4] that monochromatic light has greater defining power than light having an extended spectrum. There appear to have been differences in opinion as to the region of the spectrum having the greatest defin-

[1] *Bul. Bur. Stand.*, vol. 5, No. 2.

[2] *Elec. World*, vol. 58, p. 1252.

[3] *Elec. World*, vol. 57, p. 1103.

[4] *Elec. World*, vol. 58, p. 450.

ing power. The work of Luckiesh using monochromatic light of equal intensity throughout the spectrum appears to establish this relation fully. The results of this investigation are shown in Fig. 17. Curves I, II, and III were obtained by the investigator and represent the average of a large number of readings. The readings for curves I and II were obtained in the morning and afternoon, respectively, of the same day, and illustrate the fact that visual acuity is quite a variable function. Curve III represents the mean for the observer's eye. Curves IV and V were obtained by two other observers and represent the mean of a less number of readings. The illumination maintained throughout the experiment was 4.2 foot-candles on a surface of

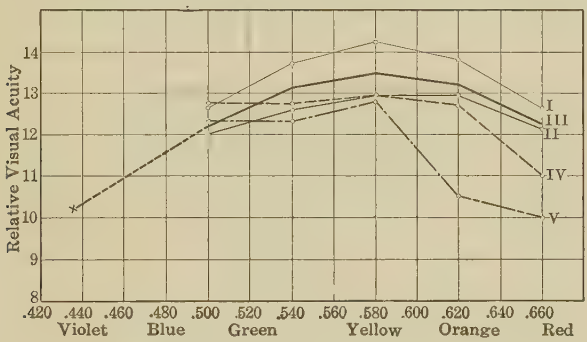


FIG. 17.—Variation of visual acuity with wave-length of light.

magnesia. This was viewed through a 2.5-mm. pupil opening and eyepiece lens, thus reducing its resultant brightness somewhat. The focusing distance of the observer's eye was about 14 in.

While it may seem to some that the acuity method is the only valid one for comparing the illuminating values of light, it must be remembered that in general illumination the results obtained by this method would not give a correct measure of the luminosity of the radiation.

In general illumination, the eye, as a rule, observes comparatively large objects which present comparatively small brightness differences, and not minimal-sized details presenting the highest practical contrast, as typical print. The fact that monochromatic light produces a more distinct retinal image does not establish the conclusion that it is the better light for constant use in distinguishing fine detail. This advantage may be more than offset by the loss of the ability to discriminate

colors. Moreover, a thorough study of the physiological effect of monochromatic light may show it to be more disturbing to the other functions of the eye than light which more clearly approaches in spectral character the natural light under which the eye has evolved.

It is only fair to state at this point that, while the mercury-vapor lamp is the nearest approach to a monochromatic source of any of the artificial illuminants, and while it is undesirable where color values are concerned, all investigations of its physiological effects which have come to the notice of the writer indicate that its light is no more harmful than that from any other illuminant.

Relative Variation of Acuity and Brightness.—In the same investigation it was found that throughout a wide range of

TABLE 11

Variation of Acuity with Brightness at Different Wave Lengths

Wave-length in $\mu\mu$	Relative brightness	Relative acuity[1]
660	1.00	1.00
	.25	.85
620	4.00	1.05
	1.00	1.00
	.25	.93
580	4.00	1.05
	1.00	1.00
	.25	.95
540	4.00	1.08
	1.00	1.00
	.25	.88
500	4.00	1.08
	1.00	1.00
	.25	.82
	1.00	1.00
	.25	.83

[1] The values of relative acuity in the last column are comparable only with those in the same group. Groups cannot be compared with each other.

illumination visual acuity varied much less than visual brightness. The relative changes of the two are shown in Table 11, where the unit of relative brightness is 4.2 foot-candles as used above. It would appear from these data that for equal variations in intensity or brightness visual acuity varies more toward the extremities of the spectrum than in the central portion.

It has been shown by Luckiesh[1] that brightness values of monochromatic light obtained by the visual-acuity method cannot be added. A red light added to a blue light will give less acuity than either source alone. This is obvious because of the want of achromatism of the eye. This point is well explained by Dow.[2] Assuming the yellow rays to be brought to a focus on the retina, the violet rays (see Fig. 18), will be brought to a

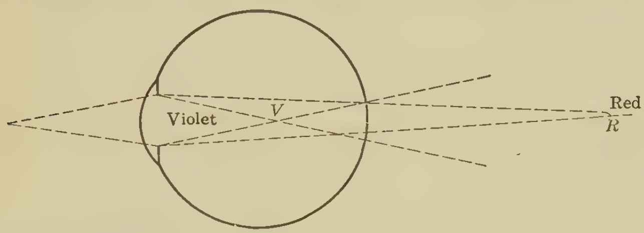


FIG. 18.—Diagram showing want of achromatism of the eye.

focus in front of it and the red rays behind it. It is obvious then that, if the eye cannot focus itself for a certain color of light, no amount of that light will make the observer see distinctly, and since it cannot focus itself for two different colors, it will doubtless focus on the resultant color of the mixture, which will not be monochromatic and, consequently, will produce less acuity.

Illumination and Perception.—The following curves[3] present basic facts which provide a direct link between better illumination and the increased production which has invariably resulted.

Figure 19 shows the relation between the level of illumination and the simplest visual operation—perception. This curve illustrates the outcome of a series of tests in which a black dot was exposed momentarily on a white field, and for each level of illumination the shortest exposure was found for which the subjects could recognize the mere presence of the dot. The curve shows that the time required for perception becomes materially

[1] *Elec. World*, vol. 58, p. 450.

[2] *Elec. World*, vol. 58, p. 955.

[3] *Ward Harrison Jour.*, A.I.E.E., vol. 43, p. 1209.

greater as the illumination is decreased below 100 foot-candles, which corresponds to the outdoor illumination on a very dark, cloudy day.

Good vision requires more than the mere perception of an object; it requires the discrimination of its fine details as well. The speed with which this discrimination can be accomplished—or, in other words, the speed of vision—involves all factors of light and lighting which influence the ability of the eye to distinguish differences in brightness, color, and fine detail. Tests similar to the "perception" tests have been conducted on the relationship between the time required for discrimination and the intensity of

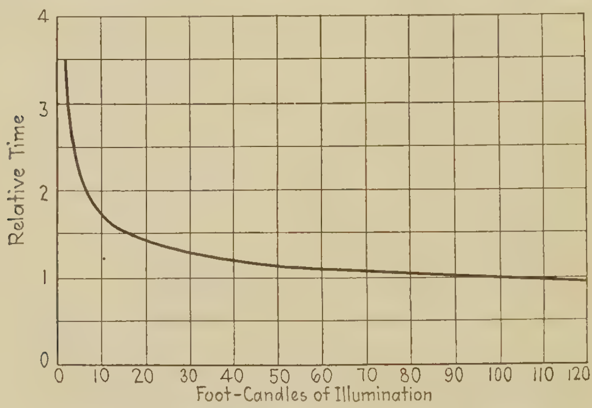


FIG. 19.—Time and light required for perception.

illumination; the results obtained show the same general trend as that noted in the curve of Fig. 20. Thus the eye discriminates details more rapidly under the higher levels of illumination, although requiring more time than for mere perception.

In the astigmatic eye, the time required for discrimination is even more dependent upon the level of illumination. This is shown very clearly by the curves in Fig. 20. These curves are confined to the range of illumination values in which the speed of discrimination changes most rapidly. Thus at the lower levels of illumination the astigmatic eye is handicapped to an even greater extent than the normal eye. Conversely, an increase in illumination benefits the astigmatic eye to a relatively greater extent than the normal eye. This fact is especially worthy of note because statistics have shown that more than half of the industrial workers of today have defective vision.

It is a common experience that under a fixed gaze the eye will become fatigued to such an extent that the detail in an object gazed at will become blurred. Tests have established this fact,

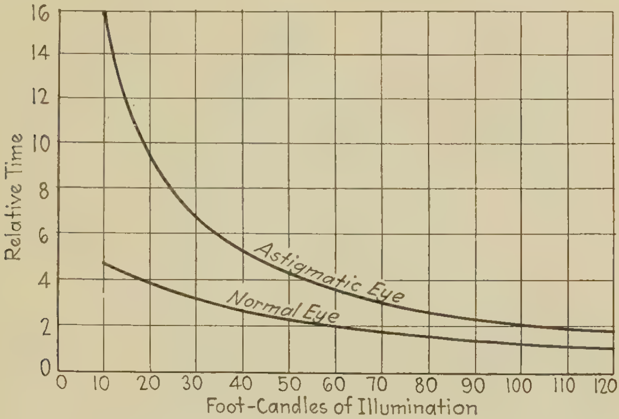


FIG. 20.—Time and light required for discrimination. Astigmatic and normal eyes.

and the results of the tests are shown in Fig. 21. Here again the astigmatic eye is handicapped even more than the normal eye by insufficient illumination. As shown by these curves, a

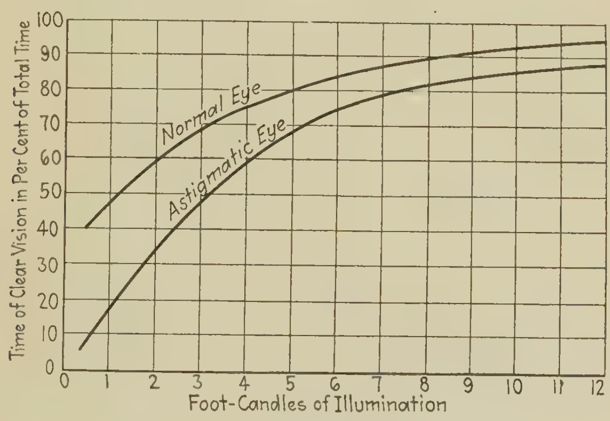


FIG. 21.—Light vs immediate fatigue for astigmatic and normal eyes. Three minute sustained vision test.

fixed gaze fatigues the eye much more rapidly when the illumination is inadequate, and defective vision also seems to aggravate tihs condition.

Brightness contrast is another factor which influences the speed of vision. Recent tests on the speed of reading involve both discrimination and brightness contrast in conditions similar to those encountered in office work and the like. Figure 22 contains the results of two such tests, which again demonstrate the fact that the speed of vision is lessened by inadequate illumination and that it also varies with the degree of contrast of an object with its background. This latter fact is significant, since in the everyday use of the eye, with the single exception of the printed page, brightness contrasts are seldom found as pronounced as black or white, which is the best condition for visual acuity.

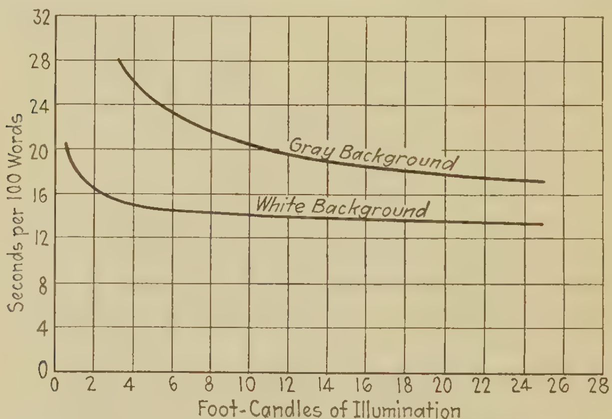


FIG. 22.—Time and light required for reading "Old English" type.

Psychological Effects.—The impressions received of light and illumination are liable to be distorted by psychological influences. Habit is likely to influence the choice or preference of particular illuminant or a particular type of installation. Public comment and personal opinions may prejudice a person. The laws of association, suggestion, attention, and expectation should be understood by the student of illuminating engineering. Any or all of these psychological peculiarities may operate to the annoyance of the practicing engineer, or may be used by him to his advantage.

Since artificial light is used for observing objects, its effectiveness is judged from the impressions which it produces. The impression is usually the result of attention, stimulated perhaps by association, suggestion, or expectation. Attention will not

attach itself firmly to uninteresting objects. It will decline if some change or some new attribute is not discovered in the object. Fatigue of the optical system results from the strain of continuous attention toward any one object, and the impression becomes less intense. This statement may easily be proved by continuing one's gaze intently upon one particular object. When attention to one object becomes exhausted, rest is obtained either by reflex attention or by directing the attention to other subjects.

Attention continuously centered upon the same subject or upon an unchanging object has been proved by experiment to tend toward either a hypnotic state or a comatose condition. Thus, in the installation of illumination systems as well as in the disposal of the areas illuminated the arrangement should be such that there will be contrast in the intensity of illumination of the objects illuminated and in the intensity of the shadows produced.

A peculiar psychological phenomenon occurs after looking at a brightly illuminated body, due to fatigue of the eye. If, for instance, after looking intently for some time at a red surface the eyes turn to a white surface, it will appear greenish-blue, or after looking through a green glass for a few moments white will appear a reddish-white. Another peculiarity of the optical system is that if alternate strips of black and white are looked at closely the white will appear much whiter by contrast with the black and a black body with a red background can be distinguished as to detail at a greater distance than if the background were green. Moreover, as *illumination grows very bright*, all colored objects incline toward a whitish-yellow tint, which must gradually modify the quality of the sensation appropriate to that particular color of light. A red surface appears brighter than a blue one in daylight, while the reverse occurs if these surfaces are viewed in weak daylight, when red may apppear black while the blue will still be visible in its proper color. In a bright light, red, orange, and yellow surfaces are relatively more brightly illuminated than blue or violet surfaces, while just the opposite relations occur in a weak light.

Flicker Effect.—In all classes of illumination a *flickering light* should be avoided, since the iris cannot keep pace with the rapid fluctuations and too little and too much light falling alternately upon the retina causes fatigue. This condition is familiar to all who have endeavored to read by the light from an open gas flame or a 25-cycle arc lamp. It has been found that if repeated

stimuli succeed each other within their period of persistence the sensation will be that of continuous light, but when the interval between the stimuli is nearly equal to the time of dying away of a sensation the light will appear to flicker. The frequency at which the flicker from an alternating source cannot be detected varies with the temperature of the luminous source and with the intensity of illumination of the object viewed.

CHAPTER III

COLOR AND ARTIFICIAL DAYLIGHT

Color plays an important part in illuminating engineering because of the physiological and psychological effects which lights of various hues produce. Not only is the acuteness of vision dependent to a certain extent upon the color of the light, but the effect of selective absorption, which so deceives the eye when colored objects are viewed by colored light, shows the necessity of a careful consideration of the color values of artificial light. Again, in comparing illuminants, the Purkinje and color effects introduce difficulties in determining their relative candle-power values. With these factors in mind, the question of a standard of color value, in terms of which the color of an illuminant may be expressed, naturally arises.

Average Daylight.—That average daylight should be accepted as a standard, in terms of which the color values of the existing sources of artificial illumination may be compared, seems to have a sound philosophical basis. The maximum of the luminosity curve of the normal eye is in the same region of the spectrum as the maximum of the radiant energy of sunlight. The organs of vision have for ages been developed, for the most part, in daylight and they are accustomed to light which possesses the spectrum of natural illumination. It only seems reasonable and rational, therefore, that the color values of illuminants should be expressed in terms of the components of average daylight.

If daylight is defined as the natural light illuminating a shaded surface, this is by no means a light of constant spectral relations. Its components will be different in different parts of the world, at different times of the year, at different times of the day, and under different atmospheric conditions. There is also a great difference in sunlight at different times of the year and at different times of the day. Of the different kinds of daylight the two most definite are the light from a *clear blue zenith sky* and *noon sunlight*, with a clear atmosphere.

By reducing the available spectrophotometric determinations of sunlight and skylight of radiant energy, Dr. Ives[1] found that:

1. Clear noon sunlight in summer corresponds closely to the energy determinations of a black body at 5000° absolute.

2. Clear blue skylight averages twice as much energy in the blue (0.450μ) as does sunlight for equal intensity in the yellow (0.590μ).

3. Light from cloudy skies varies from near blue to sunlight.

4. The light from the sun at low altitudes shows a deficiency in blue similar to the excess in blue of the clear sky.

Because of the above variations in daylight Dr. Ives suggests that the best way to arrive at an acceptable value of average daylight is to take advantage of the coincidence above stated between the maximum of sensibility of the eye and the maximum of the sun's energy as it reaches the earth through the atmosphere. Moreover, if this is not merely a coincidence but the result of adaptation, there is a criterion of average daylight which is more exact than could be obtained by any number of series of daylight measurements. Since this adaptation exists, the inference is that the most probable average daylight is the light whose spectral maximum falls in the region of maximum sensibility. This corresponds to *clear noon summer sunlight,* which is the most efficient daylight and which agrees closely with the visible radiation of a black body at 5000° absolute. Since the eye permits considerable variation in the hue of light and still gives the sensation of "white" light, the terms "average daylight" and "white light" may be used interchangeably.

With this value of daylight as a standard, Dr. Ives proceeded to investigate the color values of the artificial illuminants with reference to it. An excellent idea of the color values of an illuminant may be obtained by determining the proportion of each of the three primary colors (red, green, and blue) which must be mixed to match the visible color of the illuminant. To carry out this investigation recourse was made to the Ives colorimeter, the construction and manipulation of which are described below.

The Ives Colorimeter.—The Ives colorimeter[2] is an instrument designed by F. E. Ives for the measurement of *all colors in terms of three primary colors.* By means of the colorimeter it is

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 189.

[2] *Trans. Illum. Eng. Soc.*, vol. 3, p. 625; *Illum. Eng.*, vol. 4, p. 344.

possible to describe a color accurately in terms of the red, green, and blue components of a standard white light. If in the white light red is assumed as 100, green 100, blue 100, then the color pink may be designated as red 100, green 50, and blue 80.6. This means that by mixing red, green, and blue in the proportion here given the sensation produced in the eye is that of pink. Two colors alike to the eye measure alike in the colorimeter. The result is a means of comparing numerically the visual effect of such dissimilar sources of light as a gas flame and a mercury-vapor arc. In this respect the colorimeter differs from the spectrophotometer, which gives the intensity at every point in the spectrum but only an approximate indication of how the eye will compare the color in question with another.

The instrument consists essentially of an oblong box, at one end of which are placed four slits—one clear, the three others equipped respectively with red, green, and blue screens. By levers the openings of the three colored slits can be altered to read by scales from zero to 100. Within the instrument is a wheel of lenses, which when rotated rapidly by a small motor causes the three colors to pass across the field of vision viewed through an optical device, thus mixing them by persistence of vision. The optical arrangements are such that one observes a divided field, one part consisting of the mixture of the three primary colors, the others the color to be matched as viewed through the clear slit.

To make a measurement, the three colored slits are opened by moving the levers until white is matched, and the scales are adjusted to read 100 for each color. Then any color matched by moving the three levers can be read off the scales in terms of the per cent of red, green, or blue necessary to match white.

The colorimeter was designed to measure the color of fabrics by reflected light and when used for that purpose is manipulated as indicated above. But for measuring the color of light from a lamp, the apparatus is modified somewhat. Since there are two sources involved, the region in front of the instrument is divided by a partition and the light to be studied is allowed to fall on a flat surface of magnesium oxide placed before the clear slit. It is obvious that summer noon sunlight is not suitable for a working standard; consequently a constant comparison lamp is placed on the other side of the partition and both daylight and the other lights are measured against it, by the substitution

method. For this purpose a tungsten lamp with a frosted bulb and operating a little above normal voltage proves satisfactory. It may be placed near the colored slits and a strip of flashed opal glass will serve to diffuse and equalize the illumination of the slits.

The details of construction and operation can be better understood from Figs. 23 and 24. Figure 23 shows a side sectional

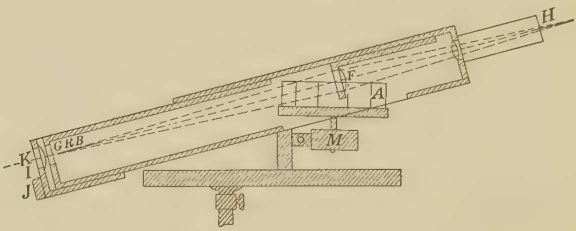


FIG. 23.—Vertical section of colorimeter.

view of the instrument. The eyepiece is at *H*, through which the observer sees a divided field, one-half of which is illuminated by a mixture of the three primary colors, and the other side by the light to be investigated. The rotating lenses are at *A* and are driven by a small motor. Focusing lenses are shown at *F* and *I*. The optical arrangement is shown by the horizontal section through the instrument in Fig. 24. The test light is admitted

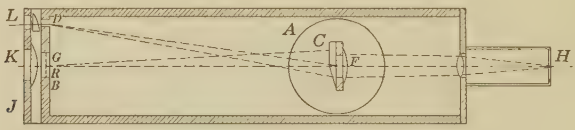


FIG. 24.—Horizontal section of colorimeter.

through the opening *L*, and the colored screens and variable diaphragms are located at *G*, *R*, and *B*.

By means of the colorimeter and with the value of average daylight equal to that of noon summer sunlight, Dr. Ives proceeded to investigate the color relationship of artificial illuminants to daylight. The values given in Table 12[1] express this relation in terms of the three primary color sensations—red, green, and blue.

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 208.

TABLE 12

Color Values of Light Sources

Source	Sensation values		
	Red	Green	Blue
1. Black body at 5000° absolute	33.3	33.3	33.3
2. Overcast sky	34.6	33.9	31.5
3. Blue sky	32.0	32.2	35.8
4. Moore carbon dioxide tube	31.3	31.0	37.7
5. Afternoon sunlight	37.7	37.3	25.0
6. Mercury-vapor arc	29.0	30.3	40.7
7. Direct-current arc	41.0	36.3	22.7
8. Welsbach mantle, 1/4 per cent. cerium	42.5	40.8	16.7
9. Welsbach mantle, 3/4 per cent. cerium	45.5	42.0	12.5
10. Welsbach mantle, 1 1/4 per cent. cerium	47.2	41.8	11.0
11. Tungsten 1.25 watts per candle	48.7	40.5	10.9
12. Nernst	49.2	40.7	10.1
13. Acetylene	49.1	40.5	10.5
14. Yellow flame arc	52.0	37.5	10.5
15. Carbon lamp, 3.1 watts per candle	51.3	40.4	8.3
16. Hefner	55.0	38.8	6.2

It will be seen from this table that nearly all illuminants give more red and green rays and less blue rays than are found in average daylight or, what is approximately the same, in light from a black body at 5000° absolute. In other words, the light is yellow. The exceptions to this are the carbon dioxide tube and the mercury-vapor arc. In studying these figures, especially those for the mercury lamp, it should be remembered that the values refer to the color of the light itself when it illuminates a white surface. The fact that some of these sources are deficient in certain of the primary colors is only apparent when viewing colored objects in their respective lights. Of all these illuminants the Moore carbon dioxide tube gives a light most closely resembling daylight. It is somewhat bluer than sunlight and less blue than skylight. Its light falls well within the visual region of white light.

The locations of these illuminants and of black bodies at different temperatures with reference to daylight are shown in the color triangle of Fig. 25[1]. The dotted line indicates the color of

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 205; *Elec. World*, vol. 57, p. 1092.

light from black bodies or incandescent solids at different temperatures up to 7000° absolute. It will be seen that nearly all of the artificial illuminants lie near this curve. The reason for the position of the carbon arc may be attributed to the blue or violet in the arc itself. Those illuminants differing from black bodies are obviously located farthest from this line. The Welsbach mantles are above the curve because of the greater amount of green due to selective radiation of energy in the visible spectrum; the flame arc, little of the light from which is due to incandescence

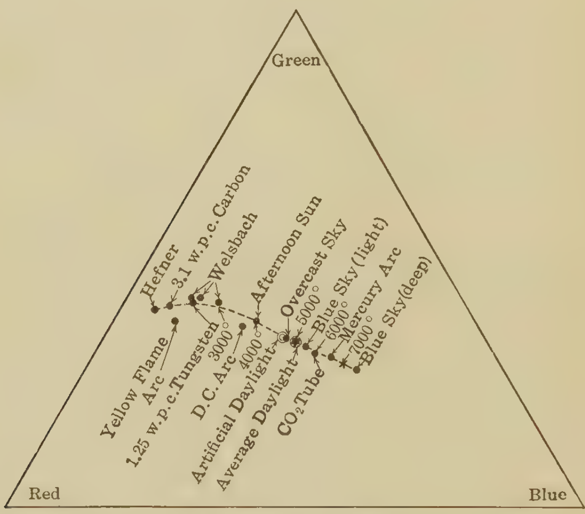


FIG. 25.—Color triangle and location of light sources.

of a solid body, lies a considerable distance from this curve; the light from the carbon dioxide tube agrees closely with that from a black body at 6000° absolute.

The question of color is of importance in interior lighting and especially so where colored merchandise is to be viewed by artificial light. In the latter class it is obvious that the color of the light should approximate as nearly as possible the color values of diffused daylight. In the lighting of a ballroom or an assembly hall, and even in residential lighting, a soft light of a yellowish hue is usually preferable, either because it is customary or because it agrees with the natural sequence—the gradual increase of red in daylight as the period of artificial lighting approaches.

Reflected Light.—The color of the light which reaches the working plane is in many cases quite different from that of the original illumination, owing to the selective reflection of surroundings. Daylight is altered considerably in spectral character by reflection from foliage, buildings, etc. Artificial light is altered in color by reflection from surroundings, such as ceilings, walls, etc. The magnitude of the latter change is obviously dependent upon the relative amount of light flux which reaches the working plane indirectly as well as upon the color of the surroundings. It is reasonable to expect greater changes in indirect than in direct systems of lighting.

The results obtained in a miniature experimental room[1] are shown in Table 13 in terms of the color of the tungsten lamp. The results may readily be transformed from this basis into any form desired. The color analyses of the yellow and green papers are given for purposes of comparison. It is seen that, by reflection from colored surroundings, the color of the useful light is quite different from that of the original illuminant. With yellow walls and ceiling, for example, the useful light was much yellower than the light from a carbon incandescent lamp.

Table 13

Colorimeter Measurements in a Miniature Room under Various Conditions

	Red	Green	Blue
1. Tungsten lamp	33.3	33.3	33.3
2. Carbon lamp, 3.1 watts per candle	38.7	34.7	26.6
3. Carbon lamp, 4 watts per candle	43.0	33.7	23.3
4. Yellow walls and ceiling, indirect	53.1	37.0	9.9
5. Yellow walls and ceiling, direct	47.6	35.7	16.7
6. Yellow walls and white ceiling, indirect	43.2	35.5	21.3
7. Yellow walls and white ceiling, direct	42.1	35.3	27.6
8. Yellow paper	43.6	38.4	18.0
9. Green paper	34.5	39.8	25.7
10. Green ceiling and green walls, indirect	35.9	43.6	17.5
11. Green ceiling and green walls, direct	36.3	37.8	25.9
12. Green walls and yellow ceiling, indirect	48.2	42.6	9.2
13. Green walls and yellow ceiling, direct	39.8	39.6	20.6
14. Green walls and white ceiling, indirect	36.6	34.1	29.3
15. Green walls and white ceiling, direct	35.2	34.6	30.2

Figure 26 shows the relative percentages of the three components in the light remaining after various successive reflections

[1] *Trans. Illum. Eng. Soc.*, vol. 8, p. 61.

from green paper. It is seen that the percentage of the green component in the reflected light rapidly increases with successive reflections, while the percentages of the other components decrease.

Artificial Daylight.—To obtain the two fairly definite and constant conditions of daylight, namely, clear noon sunlight and clear north skylight, Ives and Luckiesh[1] have adopted both the additive and the subtractive methods.

In the former case a blue-green light of the proper spectral character was added to tungsten light in proper proportion. In

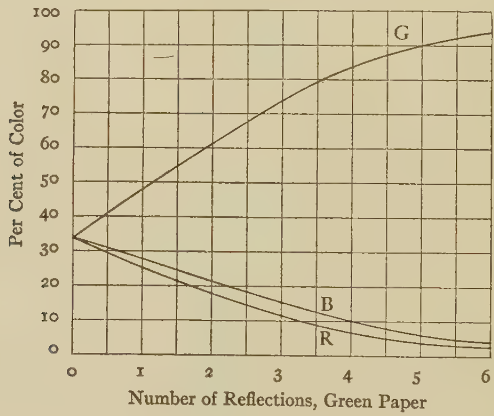


FIG. 26.—Effect of color of reflecting surface on color of reflected light.

the latter case a colored filter was used to alter the tungsten light to approximate closely a given kind of daylight.

Figure 27 shows the additive method of producing artificial noon sunlight (or average daylight). S is the spectral energy distribution in sunlight. B and A are, respectively, the energy distributions in the visible spectra of the light from tungsten lamps operating at 22 and 7.9 lumens per watt. B' and A' are complementaries to B and A. It was found that two parts of A' added to one part of A produce artificial clear noon sunlight, and equal parts of B and B' are required to accomplish the same result.

The subtractive method is the more practical. It consists in absorbing the excess of yellow and red radiation. The ideal screen should have perfect transmission at 0.42μ and a gradually

[1] *Elec. World,* vol. 57, p. 1092; *Bull. Nela Research Lab.,* vol. 1, p. 223.

increasing absorption toward the red end of the spectrum. Colored glass can be obtained having selective absorption sufficient to imitate the daylight spectrum when used with a tungsten lamp.

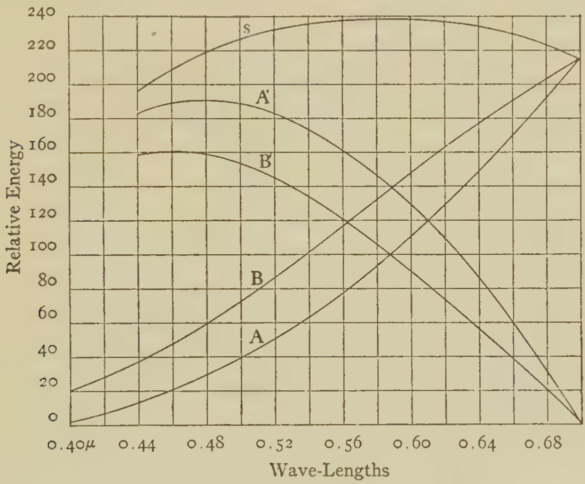


FIG. 27.—The additive method of producing artificial sunlight.

The curves showing the performance of such a combination are reproduced in Fig. 28. Curve (a) shows the transmission of an ideal absorbing medium, while (b) represents the luminosity of the light from a tungsten lamp and (c) the luminosity curve of the

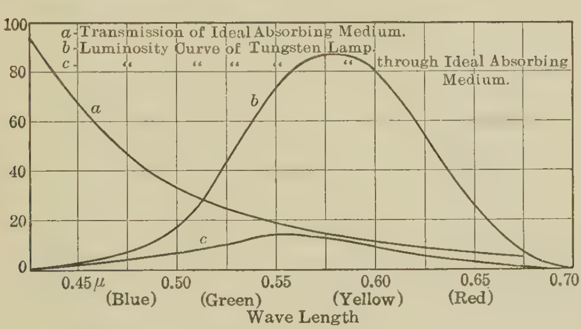


FIG. 28.—Transmission and luminosity curves for white light from a tungsten lamp.

light after passing through the absorbing medium. It will be seen that the spectrum of this transmitted light is continuous and suitable for color matching, and similar work. In this respect

it possesses an advantage over a "white" light made up by combining red, green, and blue, or yellow and blue. While a good daylight reproduction may be obtained by this latter method, the light may possess certain excess spectral bands, while other colors may be entirely missing.

For the absorbing media, cobalt blue and signal green seemed the best suited. The blue alone gave a purple light, due to the transmitted red. Signal green alone gave too green a light, but reduced the red. A combination of the two gave a pronounced band of yellow-green transmission of the cobalt. This defect was overcome by the use of a dye—rozazeine—which reduced the yellow-green band.

Only the daylight efficiencies of two tungsten lamps will be given here. The noon-sunlight efficiency of the tungsten lamp operating at 7.9 lumens per watt was found to be 14 per cent when correction is carried as far as 0.42μ. This has been found more accurate than necessary in general practice. A correction extending to only 0.45μ results in a noon-sunlight efficiency of 18 per cent. The north-skylight efficiencies for the two foregoing cases are, respectively, 4 and 9 per cent. The noon-sunlight efficiencies of the tungsten lamp operating at 22 lumens per watt, when corrected to 0.42 and 0.45μ, are, respectively, 25 and 33 per cent. The north-skylight efficiencies for the two foregoing cases are respectively 13 and 19 per cent. These corrections have been found more accurate than necessary in a great deal of color work; hence practical units have been made of higher efficiencies.

Daylight Units.—Color-matching units are now available employing type-C lamps and a blue-green glass filter plate under an efficient metal reflector. Such a unit is shown in Fig. 29. They are used for local lighting, inspecting colored material, mixing dyes, color printing, lighting color booths in silk and dress goods departments, and similar purposes. Some of the units are so designed that either artificial daylight or ordinary incandescent lighting may be obtained by the throw of a switch on the unit.

Another unit which meets a variety of needs approximates average daylight less closely, but is of high efficiency. The result is the same as that which would occur with an enormous increase in the temperature of the tungsten filament well above its melting point. This unit is known as the "daylight" lamp.

The bulb is of blue glass and the filament operates at higher temperature than the regular type-C lamp.

Experiments bearing on the relation of visibility to color and intensity were conducted using the "daylight" lamp and the type-C lamp. The tests consisted of reading *The Saturday Evening Post* and were run an average of about 40 min. for each observer. There were thirty-five observers. Each observer was free to switch from one illuminant to the other of equal wattage. Equal wattage means that with the "daylight" lamp the illumination

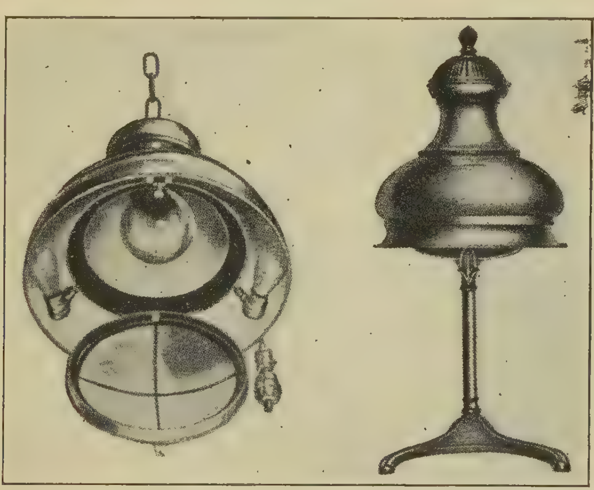


FIG. 29.—A color identification unit in which a large Mazda C lamp housed in the center produces accurate color matching light after passing through a large circular color screen at the bottom. Small Mazda B lamps at either side provide a convenient means of comparing artificial lighting color effects with daylight.

on the paper was only about two-thirds of what is was with the type-C lamp, yet the majority of observers chose the "daylight-lamp" illumination.

The Production of Colored Light.—The light emitted by the incandescent lamp has a continuous spectrum. Hence, since all colors are available in the unmodified light, there is a fortunate condition for obtaining any effect.

Suppose red light is wanted, it is necessary to subtract the complementary color (blue-green). If blue-green light is wanted, the red, orange, and yellow rays are absorbed. If the effect of orange is to be obtained, the green, blue, and violet portion is screened out. To remove any of these rays is a comparatively

simple matter. It is only necessary to pass the light through some medium which will absorb the particular part or parts which it is desired to remove.

To obtain the same illumination with colored light, two, three, or fifty times the wattage must be used in comparison with that used for unmodified light. Table 14 gives some approximate figures on the absorption or loss of light necessary to obtain various colors of light from the incandescent lamp. These values are subject to considerable variation, depending on the purity of color secured and other factors.

Table 14

Ordinary designation	Absorption, per cent	Transmission, per cent	Wattage to produce same illumination as with unmodified light, per cent
Red	85–75	15–25	400 to 600
Orange	70–50	30–50	200 to 300
Yellow	40–20	60–80	125 to 150
Green	80–90	10–20	500 to 1,000
Blue	95–90	5–10	1,000 to 2,000
Purple	98–95	2–5	2,000 to 5,000

Fortunately, high level of colored lighting is rarely required.

Gelatin color screens are available in a wide variety of tints and shades. They are, therefore, especially of service in producing delicate gradations of color. The gelatin material is rather difficult to manipulate, being affected by moisture and extreme heat or cold. The screens break easily and the life of the screen in service is rather short. Where used across the mouth of reflectors or in border and strip lights, special precautions must be taken to have a reliable holding device to prevent the gelatin from curling, opening a gap, and allowing unmodified light to escape, spoiling the effect. A network of fine wire overcomes this difficulty.

Colored Lighting.—In order to use colored lighting intelligently, a knowledge of certain comparatively simple fundamentals is necessary. It must be remembered that an object is seen by the light it reflects to the eye. A *pure* red light falling on a red object

will be reflected in full color; falling on a green object will be absorbed, and the object, reflecting no light, will appear black; falling on a yellow object, the object will appear red, because yellow reflects red among other colors.

It is rare, in practice, that pure colors are encountered, either in light or in pigments. The general effects are, however, of the order indicated.

The commercial reds (glasses, dips, and gelatin screens) are usually quite pure; the greens frequently contain blue, yellow, and even a trace of red. The blues are likely to contain all the colors, blue, of course, predominating. In practice, therefore, before making the actual installation, it is desirable to experiment with both the colored light and the pigment intended for use on the scenery or decoration. By manipulation and correct choice of material, a desirable effect can be secured.

(*a*) (*b*) (*c*)

FIG. 30.—This illustrates, in a crude manner, the effect of colored light on colored objects. The foliage on the trees is green, the trunks and branches are red.

(*a*) The appearance when illuminated with white light.
(*b*) The appearance when illuminated with green light.
(*c*) The appearance when illuminated with red light.

The action of colored light on colored material is of importance in decorative lighting and on the stage. By the proper combination of colored light and painted scenery, it is possible to change a scene entirely, without manipulating any scenery. This effect is based on the following principle:

If a red object on a white background is illuminated with red light, the background and the object will both reflect red light in its full value. There will be no contrast or difference in brightness, and the object will be invisible. Similarly, green light falling on a green object on a white background will cause the object to fade out.

Figure 30 shows, in a crude manner, the effect just discussed. In this illustration the foliage on the trees is green, the trunks and the branches are red. Illuminated with white light, the foliage

TABLE 15

Color of Incident Light Results

Original color	Red light	Orange light	Yellow light	Green light	Blue light	Violet light
Black	Purplish-black	Deep maroon	Olive-yellow	Greenish-brown	Blue-black	Faint violet-black
White	Red	Orange	Light yellow	Green	Blue	Violet
Red	Intense red	Scarlet	Orange	Brown	Violet	Reddish-violet
Orange	Orange-red	Intense orange	Yellow-orange	Faint greenish-yellow	Violet-brown	Light red
Yellow	Orange	Yellow-orange	Orange-yellow	Yellowish-green	Green	Brown, faintly red
Light green	Reddish-gray	Yellow-green	Greenish-yellow	Intense green	Blue-green	Light purple
Deep green	Reddish-black	Rusty green	Yellowish-green	Deep intense green	Greenish-blue	Bluish-gray
Light blue	Violet	Orange-gray	Yellowish-green	Green-blue	Vivid blue	Violet-blue
Deep blue	Violet-purple	Orange-gray	Green-slate	Blue-green	Intenser blue	Bright blue-violet
Indigo blue	Purple, slightly violet	Orange-maroon	Dull orange-yellow	Dull green	Dark indigo blue	Deep blue-violet
Violet	Purple	Red-maroon	Yellow-maroon	Bluish-green-brown	Deep bluish-violet	Deep violet

will appear green and the limbs red. If this is illuminated with green light (or viewed through green spectacles), the foliage fades into the background and the bare branches appear black or a dark brown. If it is illuminated with red light, the foliage appears brownish and the limbs are practically invisible. This crude example is purposely simple, but with experimentation the principle can be extended to produce truly marvelous effects.

An idea of the effect produced when colored light is thrown on objects of different colors can be obtained from Table 15.

CHAPTER IV

PHOTOMETRIC STANDARDS, UNITS, AND NOMENCLATURE

Standards of luminous intensity or candle power are devices for producing visible radiation of constant and measurable value. Those existing or proposed secure this constancy of luminous radiation by three methods:

1. By the first method the flame standards are used. In the construction and use of this class certain specifications are closely followed, and their accuracy is based on the assumption that if these specifications are followed the standard intensity will be reproduced. These specifications refer to such details as the size, material, and weave of the wick, the size and construction of the burner and chimney, the composition and rate of combustion of the fuel, and the pressure and humidity of the atmosphere.

2. By the second method the intensity of radiation is controlled by the observation or measurement of some accompanying physical variable, such as temperature. The Violle platinum standard, the arc standard, and the black-body standard belong to this class.

3. By the third method it is proposed that the intensity of visible radiation be controlled by the direct measurement of the radiation, as radiation. To this class belong the three spectral line standard proposed by Steinmetz and the "definite quantity of the most efficient possible radiation" standard proposed by Ives.

The standard of luminous intensity was, for a time, the light of a candle made to certain specifications and consumed at a given rate; and it has been the almost universal custom to refer the intensity of a light source to that of the candle and to give the value of its luminous intensity in terms of the candle or candle power.

The flame standards of luminous intensity which have been used to quite an extent in the past are the English and German

candles, the Carcel lamp, the Methven screen, the kerosene standard, the pentane standard, and the Hefner lamp.

Since seasoned incandescent lamps properly certified have replaced the flame standards for photometric work, and since a description of the various flame standards may be found in any of the books on photometry, of an earlier date, only the Hefner lamp will be described here.

The Hefner Lamp.—The most successful primary flame standard is the Hefner amyl acetate lamp. This lamp is especially

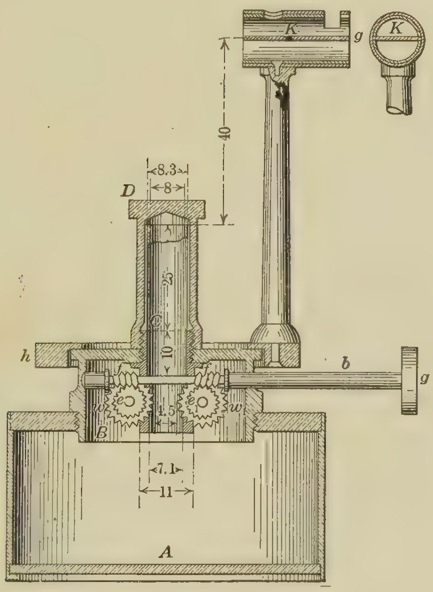


FIG. 31.—The Hefner lamp.

favored in Germany and is the official standard recognized by the Physikalisch-Technische Reichsanstalt. It has been sub. jected to thorough and accurate investigations and its faults as well as its merits are clearly understood.

The Reichsanstalt lamp has been universally adopted as the standard for the use of amyl acetate. The lamp is constructed of brass, except for the wick tube, which is of German silver to prevent corrosion by the combustible. The wick is moved by a worm gear, which actuates two spur wheels, shown in Fig. 31. All the fittings of the lamp are attached to the wick tube, which

unscrews from the cup for filling. The character of the wick has practically no influence on the candle power of the lamp, since amyl acetate vaporizes at such a low temperature that the wick does not project into the flame and burn. A metal cap is kept screwed down over this wick when the lamp is not in use.

A test gage is furnished with each lamp for adjusting the height of the flame, which burns with greatest constancy and steadiness when about 40 mm. in height. Accuracy in setting the flame is essential, since a variation of 1 mm. in height will produce about 3 per cent difference in the illuminating power. Under the above conditions and with normal atmospheric pressure and humidity the horizontal intensity of the flame is 0.9 candle power.

It was also found that an increase or decrease of 1 mm. in the diameter of the wick tube caused a variation of 1 per cent in the light intensity.

Herr von Hefner-Alteneck, the inventor of this lamp, pointed out and insisted on the necessity of using a combustible of known chemical composition. Amyl acetate ($C_7H_{14}O_2$), because of its chemical simplicity and definite composition, is excellent as the combustible of a standard. It is a colorless liquid, and burns with a clear, not very brilliant, somewhat reddish flame; it is obtained from the distillation of amyl alcohol, obtained from fusil oil, with a mixture of acetic and sulphuric acids, or by distilling a mixture of ethyl alcohol, sulphuric acid, and potassium acetate. Impurities, which are most common in amyl acetate, have little effect upon the value of the light from this lamp.

Amyl acetate should be kept in a glass-stoppered bottle and, as it has a tendency to decompose in strong light, it should be stored in a dark place, or in opaque vessels.

The temperatures produced by the lamp itself are rendered negligible by the thinness of the walls of the tube, while atmospheric temperatures have no discernible influences.

Atmospheric moisture, however, is not without its effect. Data showing the monthly averages for the light of the Hefner lamp for 1 year vary from 101.9 per cent normal candle power for February to 97 per cent for July. During March, April, May, October, and November the average intensity was normal. For June, July, August, and September the average was about 2 per cent below normal, and for December, January, and February the average was about 2 per cent high. The results of tests extending through 2 years showed a maximum difference of 8.5

per cent, or 103.3 per cent in January and February, and 94.8 per cent in May and July. Hence this lamp can be relied upon to give values within 4 per cent of the normal standard candle power.

Analyzing and combining all the experimental data on the relation between the candle power of the Hefner lamp, the humidity, and the barometric pressure, the following equation was decided upon:

$$y = 1 - 0.0055(x - 88) + c_2'(b - 760) - c_2''(b - 760)^2,$$

where y is the candle power of the lamp, x the liters of water vapor per cubic meter of dry air, b the barometric pressure, c_2' equals 0.00015, and c_2'', 0.0000019. Tests as to the accuracy and constancy of the Hefner lamp have given satisfactory results. The chief objection to this lamp as a standard is that the flame is too red, thus making it possible to introduce errors in photometry.

The Violle Platinum Standard.—The Violle standard consisted of the luminous radiation from 1 sq. cm. of incandescent platinum at the temperature of liquefaction. In some of the earlier investigations of this standard a lower temperature was used, but under these conditions it proved unsatisfactory. The rapid disintegration of the platinum gave considerable change in temperature for a given value of current. This unit, however, has much to recommend it. The temperature of the melting point of a pure metal can be accurately defined and reproduced. The composition of the light from melting platinum corresponds more nearly to that from modern light sources than does the light from the other standards previously mentioned. The larger value (20 bougies or candles) is another advantage. Experiments by Petanel,[1] in which he used hydrogen instead of coal gas in the blast lamp for melting the platinum, indicate that Violle's standard is neither impractical nor inaccurate.

The *Bougie candle* is equal to 0.05 of the Violle standard, or to the light from 5 sq. mm. of incandescent platinum at the temperature of liquefaction.

The Arc Standard.—The arc standard is the name applied to a standard in which it is proposed to use the light from the positive crater of a carbon arc. It has been found that the intrinsic brightness of the positive crater between pure carbon electrodes

[1] *Proc. Roy. Soc.*, vol. 65, p. 469.

possesses remarkable constancy with varying specific consumptions of energy.[1] The question of reproducibility appears to be dependent only on the location of the crater and the use of a standard quality of carbon electrode.

The Black-body Standard.—It has been proposed to define the unit of light as the physiological effect of the equivalent of 1 watt of visible radiation. Since this assumption requires a definition of the distribution of energy throughout the visible region, it was further suggested to accept the visible radiation from a black body at such a temperature that the ratio of the radiation in two definite regions of the spectrum have a specified relation as such a definition.

It is obvious that such a source possesses unfavorable characteristics, such as the deviation of the radiator from a black body; unequal absorption of the glass envelope to energy of different wave lengths; liability of inaccuracy in locating the proper limit in the red portion which would seriously affect the results because of the magnitude of the radiation in this region compared with the physiological effect; and the color of the light, which must be yellow instead of white because of the temperature limitations imposed by the radiator.

Object of a Primary Standard.—The object of the primary standard is, obviously, not to obtain a working standard for laboratory purposes, but rather a reproducible unit to which reference may be made from time to time to prevent any drifting in one way or another which is likely to occur in the status of the arbitrary standard of luminous intensity in vogue at the present time. None of the primary standards already mentioned are by any means satisfactory, both from the scientific and from the practical sides. They are in no way connected with the fundamental units of space, mass, and time. Until thus coordinated, they can be considered as little more than convenient arbitrary references to be used in practice, pending the determinations of their real values.

The sensation of light is caused by the impinging of radiant energy upon the retina; consequently, it seems only logical that the scientific specifications for the standard of light should be based on the measurement of radiation.

The complexities and difficulties arising in connection with the development of such a standard are obvious. It was shown

[1] *Proc. Roy. Soc.*, vol. 27, p. 157; *Bull. Bur. Stand.*, vol. 1, p. 109.

in the preceding chapter that mere intensity of radiation is not an indication of luminous intensity, for not only is a large part of the radiation from most artificial light sources invisible, but even the visible part varies greatly in effectiveness in producing the sensation of brightness. Moreover, the mode of action of the eye is such that the luminous equivalent of radiation of a certain spectral wave length varies with the absolute intensity.

The Proposed Radiation Standard.—A primary standard based on the measurement of radiation was proposed by Dr. Steinmetz[1] in 1908. He suggested the selection and mixture of three primary colors of the visible spectrum, namely blue, green, and red, in definite proportions, so chosen as to give a white or yellowish-white light. A comprehensive treatment of possible standards of this type is given in a paper by Dr. Ives,[2] to which the reader is referred for greater details. In this paper it is stated, in reference to a possible three-line standard, that, from the standpoint of purity in respect to the primary sensations, the colors possessing the nearest claims to primary colors are a red of greater wave length than 0.64μ, a green of 0.506μ, and a blue of 0.48μ. These wave lengths are almost exactly furnished by an arc between cadmium electrodes. Moreover, it is these three cadmium lines, red (0.6439μ), green (0.5086μ), and blue (0.4800μ), that are the standards of wave length in terms of which the standard meter bar at Paris has been calibrated by Michelson. It is suggested that, if a three-line standard ever be considered seriously, it would be well to consider the advisability of having the same source which furnishes our ultimate standard of length also furnish our ultimate standard of luminous intensity.

While the three-line standard permits the making of a standard of any desired color, the specification of the radiation-light relationship is complicated, and spectroscopic, radiometric, and photometric difficulties render it probably impractical.

Dr. Ives suggests as a standard a *definite quantity of the most efficient possible radiation.* This could be achieved practically by measuring both as radiation and light a monochromatic radiation whose luminous efficiency is known. The green radiation of mercury actually corresponds, within the limits of present measurements, to the most efficient possible radiation and suggests itself as a practical means of obtaining this standard.

[1] *Trans. Am. Inst. Elec. Eng.*, vol. 27, p. 1319.

[2] *Trans. Illum. Eng. Soc.*, vol. 6, p. 258.

It may be obtained from the quartz mercury arc in sufficient quantity for both radiometric and photometric purposes and may be easily isolated by color screens. No spectroscopic device is necessary for separating this line from the others. A sheet of neodymium glass will obstruct the neighboring yellow lines. A solution of potassium bichromate in a glass trough will obstruct the blue, violet, and ultra-violet radiation.

Thus an absorption cell can be easily prepared through which green radiation will pass in great intensity and purity.

Such a standard has much in its favor. Compared with a three- or two-line standard its theoretical simplicity is evident. It possesses the simplest possible relationship between radiation and light. Its establishment as a primary standard would make the unit of light the watt per square centimeter of the most efficient possible radiation. The lumens emitted by any given source would be obtained at once by multiplying its consumption in watts by the "reduced luminous efficiency" of the source.

Recently also Houstoun[1] and Strache[2] have suggested the specification of a standard in terms of radiation weighted as light. Houstoun would do this by a special absorbing screen, Strache by a template over the spectrum. Parts of the spectrum are then recombined. Both of these suggestions, when analyzed, consist in specifying the light standard by the least quantity of radiated energy which can produce the standard intensity.

The Incandescent Lamp as a Comparison Standard.—The incandescent lamp, aside from its illuminating value, is of inestimable value as a secondary or comparison standard of light. The incandescent lamp has probably been of more service in photometry than any other source of light, because of the constancy of the luminous intensity of a particular filament under proper conditions. This attribute has made possible concordant data and a quantitative knowledge of the variations in flame standards. The color of the light from an incandescent lamp, especially if the lamp has a metallic filament, can be varied by changing the voltage so as to resemble the compared light in nearly all cases. They may be moved along the photometer bar at the pleasure of the operator and are portable, making them convenient in portable photometers, where a low-voltage lamp may be used in conjunction with a storage cell.

[1] *Proc. Roy. Soc.*, vol. 85, p. 275.

[2] *Zeit. Beleuchtungsw.*, 1911.

When possible, the illuminating power of a lamp to be used as a standard should be determined by comparison with the standards maintained at the Bureau of Standards or some laboratory qualified to do this work. It is well to keep one or more carefully standardized lamps for occasionally checking the working standards. The temporary set or hysteresis in the resistance of the filament, and especially the permanent set due to abnormally high voltages, should be avoided. A lamp should not have voltages impressed upon it much in excess of that at which it is aged and calibrated.

It is necessary to know the position of the lamp relative to the photometric axis when being standardized, and the voltage, current, or wattage at which it was standardized, in order to be able to reproduce known conditions. Incandescent lamps are usually operated as standards at a constant voltage, the current being used as a check. Sometimes they are operated at constant current and the voltage varied slightly if necessary. The method would be immaterial, provided there was no change in the resistance of the filament during its period of operation. But since the resistance of a carbon filament decreases during the first part of its life and increases during the later periods, it becomes a question of importance whether the best performance of a lamp can be secured during its useful life as a standard by operating it at constant voltage, constant current, or constant wattage. It is obvious that the most constant candle power would be obtained by operating the lamp at constant wattage if no change in the surface of the filament or blackening of the bulb occurred, since at a constant rate of energy supply there would result a constant light flux. But it is well known that there is a change in the surface of the filament and a greater or less increase in the absorption of the bulb due to blackening, which cause a decrease in candle power during the life of a lamp.

At constant voltage the candle power will increase during the period of decreasing resistance and decrease after the resistance has become a minimum. At constant current the candle power decreases till the resistance becomes a minimum and then increases, but the blackening of the bulb, and the decrease in emissivity of the filament decrease the candle power and counterbalance, to some extent, the increase in candle power at constant current due to the increase in the resistance of the filament.

From the above it may be expected that the life performance with respect to intensity will be more constant at constant wattage, and such a decision is corroborated by the results of experimental tests, which show that the best performance of a standard will be obtained by operating it at such voltage or current as to maintain the watts constant. In a carbon-filament lamp there is slightly less liability of error due to voltage fluctuations by maintaining the watts constant by means of the current, because of the negative temperature coefficient of resistivity of the carbon filament.

The carbon lamp was used most extensively as a secondary standard, but the tungsten lamp possesses properties more favorable and characteristics more desirable for a secondary or working standard of luminous intensity. The advantages of the tungsten lamp are: (1) the greater constancy of candle power through its useful life, even when operating at its normal efficacy; (2) the greater range in color values which it is possible to obtain without subjecting the lamp to abnormal conditions; and (3) less variations in candle power with changes in voltage because of the positive temperature coefficient of resistivity. Reports of cases where this lamp has been used as a working standard are most favorable and indicate an extensive adoption for this class of work. Unlike the carbon lamp, it is obvious that greater constancy of intensity at constant wattage may be maintained with fluctuating voltage through the agency of the electromotive force than by means of the current because of the positive temperature coefficient.

It can be seen from the life curves of incandescent lamps that a lamp is not suitable for a standard until it has been in operation for 50 or 100 hr. After burning about this length of time its performance becomes less variable, and it is at this period of its existence that it should be standardized.

In photometry it often becomes desirable, where exact voltage regulation is impossible, to correct the values of intensity obtained for variations in voltage. In order to do this, a knowledge of the performance of the unit under those conditions becomes desirable. It has been found that for incandescent lamps the intensity can be represented over a small range by the equation

$$I = aV^k, \tag{15}$$

where I is the candle power, V the voltage, and a and k are con-

stants. If I_o be the candle power at a voltage V_o, then the candle power I_x at some other voltage E_x may be found by the expression

$$I_x = \left(\frac{V_x}{V_o}\right)^k I_o. \tag{16}$$

The value of k for a tungsten-filament lamp is 3.51, based on a fundamental efficiency of 10 lumens per watt. For the 3.1-w.p.m.h.c.p. carbon lamp the value of k is 5.4.

The units of illumination and photometry in vogue in this country are based on a system of units adopted at the International Congress of Electricians at Geneva in 1896.

This assembly accepted the bougie (candle) as the unit of luminous intensity, which unit should be equal to the luminous intensity of 5 sq. mm. of incandescent platinum at the point of solidification. This was intended to be one-twentieth of the Violle standard, which consisted of 1 sq. cm. of platinum under the same conditions.

The unit of illumination intensity was termed the lux and was that intensity of light on a normal plane 1 m. away from a source of 1 bougie.

The lumen or unit of flux was that light on 1 sq. m. having a uniform intensity of 1 lux.

The lumen-hour was the product of unit flux by unit time.

These units have been modified somewhat and new terms and definitions added to clarify the relations between the various photometric quantities.

Due to an international agreement between the national laboratories and many of the interested engineering organizations of England, Germany, France, and the United States, a common unit of candle power, known as the "international candle," came into existence in 1909.

Consequently, the unit of candle power in this country became of the same value as the unit of England, the bougie candle of France, and 1.11 times the Hefner unit of Germany. Therefore the Hefner unit is equal to 0.90 of the candle.

On the following pages are presented the list of units, definitions, and abbreviations recommended by the Committee on Nomenclature and Standards of the Illuminating Engineering Society, as revised in 1923.

DEFINITIONS AND UNITS

1. *Light.*—The term light is used in various ways:

(1) To express the visual sensation produced normally when radiant flux within the proper limits of wave length, of sufficient intensity and of sufficient duration, impinges on the retina.

(2) To denote the luminous flux which produces the visual sensation.

(3) By extension, even to denote radiant flux of wave lengths outside of the visible spectrum (*e.g.*, ultra-violet light).

2. *Radiant flux* is the rate of energy radiation, and is expressed in ergs per second or in watts.

3. *Luminous flux* is the rate of energy radiation evaluated with reference to visual sensation.

(Although luminous flux must strictly be defined as a rate, in practice it is often referred to as if it were an entity or quantity.)

4. *Lumen.*—The unit of luminous flux is the Lumen. It is equal to the flux, through a unit solid angle (steradian) from a uniform source of 1 international candle.

5. *The luminous intensity* of a source in any direction is the flux per unit solid angle (steradian) from the source in that direction.

(The flux from any source of dimensions which are negligibly small by comparison with the distance at which it is observed may be treated as if it were emitted from a point.)

6. *International Candle.*—The unit of luminous intensity is the International Candle, such as has resulted from international agreement between the three national standardizing laboratories of France, Great Britain, and the United States in 1909.

This unit is conserved by means of incandescent electric lamps in the laboratories which remain charged with its conservation.

7. *Candle power* is luminous intensity expressed in candles.

8. *Illumination* at any point of a surface is the luminous flux density at that point, or, when the illumination is uniform, the flux per unit of intercepting area.

9. *Lux.*—The practical international unit of illumination is the Lux. It is equal to 1 lumen per square meter, or it is the direct illumination on a surface which is everywhere 1 m. from a uniform point source of 1 international candle.

(As a consequence of certain recognized usages, the illumination can also be expressed by means of the units, phot and foot-candle.)

10. *Phot.*—Using the centimeter as the unit of length, the unit of illumination is 1 lumen per square centimeter, and is called the Phot.

11. *Foot-candle.*—Using the foot as the unit of length, the unit of illumination is 1 lumen per square foot, and is called the Foot-candle.

12. *Lighting.*—The time integral of luminous flux is designated by the term lighting.

13. *The Lumen-hour* is the unit of lighting. It is the lighting represented by a rate of 1 lumen continued for 1 hr.

14. *Exposure* is the product of an illumination by the time.

The microphot-second (0.000,001 phot-second) is a convenient unit for a photographic plate exposure.

15. *Brightness* of a surface is the luminous intensity per unit of projected area.

16. *Units of Brightness.*—The C.G.S. unit of brightness is 1 candle per square centimeter of projected area. In the English system the unit of brightness is 1 candle per square inch of projected area.

(A surface of unit brightness emits 1 lumen per steradian per unit of projected area.)

17. *The lambert* is a practical unit of brightness. It is equal to a brightness of $1/\pi$ candle per square centimeter of projected area. It is the average brightness of a surface emitting or reflecting 1 lumen per square centimeter, or the uniform brightness of a perfectly diffusing surface emitting or reflecting 1 lumen per square centimeter.

For most purposes the millilambert, 0.001 lambert, is the preferable practical unit.

(Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.487$.

A perfectly diffusing surface emitting 1 lumen per square foot will have a uniform brightness of 1.076 millilamberts.

In practice, no surface obeys exactly the cosine law of emission or reflection; hence the brightness of a surface generally is not uniform, but varies with the angle at which it is viewed.)

18. *Visibility* of radiation of a particular wave length is the ratio of the luminous flux at that wave length to the corresponding radiant flux.

19. *Visibility Values.*—The following values for visibility and for relative visibility (maximum visibility being taken for the purpose as unity) are recommended (see Table 16).

Table 16

Visibility of Radiation

Wave length, μ	Visibility of radiation, average normal eye	
	Relative to that at 556μ	Absolute, lumens per watt
400	0.0004	0.3
10	0.0012	0.8
20	0.0040	2.7
30	0.0116	7.7
40	0.023	15
450	0.038	25
60	0.060	40
70	0.091	61
80	0.139	93
90	0.208	139
500	0.323	215
10	0.484	323
20	0.670	447
30	0.836	557
40	0.942	628
550	0.993	662
60	0.996	664
70	0.952	635
80	0.870	580
90	0.757	505
600	0.631	421
10	0.503	335
20	0.380	253
30	0.262	175
40	0.170	113
650	0.103	69
60	0.059	39
70	0.030	20
80	0.016	10.7
90	0.0081	5.4
700	0.0041	2.7
10	0.0021	1.4
20	0.0010	0.67
30	0.00052	0.35
40	0.00025	0.17
750	0.00012	0.08
60	0.00006	0.04

20. *The mechanical equivalent of light* is the ratio of radiant flux to luminous flux for the wave length of maximum visibility, and is expressed in ergs per second per lumen, or in watts per lumen. It is the reciprocal of the maximum absolute visibility.

As a standard value for the mechanical equivalent of light, the figure 0.0015 watt per lumen is recommended.

(This term has been used in a variety of senses. As here defined, it refers only to the minimum mechanical equivalent of light and corresponds to monochromatic light of maximum visibility. The reciprocal of this quantity is sometimes called the luminous equivalent of radiation.)

21. *A luminosity curve* of a source of light is a curve showing for each wave length the luminous flux per element of wave length. Therefore it gives, wave length by wave length, the product of the radiant flux and the visibility.

22. *The luminous efficiency* of any source is the ratio of the luminous flux to the radiant flux from the source. For practical purposes it is usually expressed in lumens per watt radiated.

23. *The quality of luminous flux* is that property of luminous flux determined by its spectral distribution.

24. *The color of luminous flux* is the subjective evaluation by the eye of the quality of luminous flux. Any color can be expressed in terms of its hue and saturation.

25. *Hue* is that property of color by which the various spectral regions are characteristically distinguished. All colors except purples and white may be matched in hue with spectral colors. In the case of a purple, the spectral hue which is complementary to the hue of the purple is ordinarily used for scientific designation.

26. *Two hues are complementary* if they may be mixed to produce white. White may be considered as a color having no hue. By the mixture of luminous fluxes of two or more hues properly chosen both as to hue and intensity, a resultant luminous flux may be obtained which has the color white. Whenever luminous fluxes of two or more hues are mixed, the resultant luminous flux, though it may have some dominant hue, will ordinarily be evaluated subjectively as having an admixture of white.

27. *The saturation of a color* is its degree of freedom from admixture with white. Monochromatic spectral light may, for purposes of measurement, be considered as having a saturation of 100 per cent. As white light is added, the saturation decreases, until, when the hue entirely disappears, the saturation is zero. White therefore is the limiting color, having no hue and zero saturation.

28. *Diffusing* surfaces and media are those which break up the incident flux and distribute it more or less in accordance with the cosine law, as, for example, white plaster and opal glass.

29. *Redirecting* surfaces and media are those which change the direction of the luminous flux in a definite manner, as, for example, a mirror or a lens.

30. *Scattering* surfaces and media are those which redirect the luminous flux and break it up into a multiplicity of separate pencils, as, for example, ripple glass, reflecting or transmitting.

31. *The reflection factor* of a body, ρ, is the ratio of the flux reflected by the body to the flux incident upon it. The reflection from a body may be

regular, diffuse, or mixed. In regular reflection the flux is reflected at an angle of reflection equal to the angle of incidence. In diffuse reflection the flux is reflected in all directions. In perfectly diffuse reflection, the distribution of the reflected flux is in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

32. *The regular reflection factor* of a body is the ratio of the regularly reflected flux to the incident flux.

33. *The diffuse reflection factor* of a body is the ratio of the diffusely reflected flux to the incident flux.

34. *The absorption factor* of a body, α, is the ratio of the flux absorbed by the body to the flux incident upon it.

35. *The transmission factor* of a body, τ, is the ratio of flux transmitted by the body to the flux incident upon it.

$$\rho + \alpha + \tau = 1.$$

36. *Unidirectional* illumination on a surface is that produced by a single light source of relatively small dimensions. It is characterized by the fact that a small opaque object placed near the illuminated surface casts a sharp shadow.

37. *Multidirectional* illumination on a surface is that produced by several separated light sources of relatively small area. It is characterized by the fact that a small opaque object placed near the illuminated surface casts several shadows.

38. *Diffused* illumination is that produced either by primary or secondary light sources having dimensions relatively large with respect to the distance from the point illuminated, and scattering light in all directions. It is characterized by relative lack of shadow. Diffused illumination may be derived principally from a single direction as in the light from a sky-lit window, or from all directions, as in the open air. Perfectly diffused illumination on a surface is shadowless.

In any practical case of illumination on a surface there is usually a mixture of the above types.

39. *The coefficient of utilization* of an illumination installation on a given plane is the total flux received by that plane divided by the total flux from the lamps illuminating it. When not otherwise specified, the plane of reference is assumed to be a horizontal plane 30 in. (76 cm.) from the floor.

40. *The variation factor* of an illumination installation is the ratio of either the maximum or the minimum illumination on a given plane to the average illumination on that plane.

41. *The variation range* of illumination on a given plane is the ratio of the maximum illumination to the minimum illumination on that plane.

42. *The hemispherical ratio* for a given lighting unit is the ratio of the luminous flux in the upper hemisphere to that in the lower hemisphere.

43. *The brightness ratio* is the ratio of the brightness of any two surfaces. When the two surfaces are opposed, the brightness ratio is commonly called the "brightness contrast."

44. *Lamp*, a generic term for an artificial source of light. The following definition has been agreed to conjointly with the Lighting Division of the Standards Committee of the Society of Automotive Engineers:

45. *An electric incandescent lamp* is a light source consisting of a glass bulb containing a filament electrically maintained at incandescence. A lighting unit consisting of an electric incandescent lamp with shade, reflector, enclosing globe, housing, or other accessories is also commonly called a "lamp." In such cases in order to distinguish between the assembled lighting unit and the incandescent light source within it, the latter is often called a "bulb," especially in the automobile industry.

46. *The output* of all illuminants should be expressed in lumens.

47. *Illuminants should be rated* upon a lumen basis rather than a candlepower basis.

48. *Lamp efficiency* is the ratio of the luminous flux output to the power input.

49. *The lamp efficiency* or *specific output of electric lamps* should be stated in terms of lumens per watt and that of illuminants depending upon combustion should be stated in lumens per British thermal unit per hour.

50. *The power consumption of auxiliary devices* which are necessarily employed in circuit with a lamp should be included in the input of the lamp. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

51. *The specific consumption* of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horizontal candle.

52. *Life Tests.*—Electric incandescent lamps of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

53. *In comparing different luminous sources,* not only should their candle power be compared, but also their relative form, brightness, distribution of illumination, and character of light.

54. *Lamp Accessories.*—*A reflector* is an appliance the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

55. *A shade* is an appliance the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

56. *A globe* is an enclosing appliance of clear or diffusing material the chief use of which is either to protect the lamp or to diffuse its light.

57. *A luminaire* is a complete lighting unit consisting of a light source, together with its direct appurtenances, such as globe, reflector, refractor, housing, and support. The term is used to designate lighting fixtures, wall brackets, portable lamps, or so-called removable units.

58. *A primary luminous standard* is one by which the unit of light is established and from which the values of other standards are derived. A satisfactory primary standard must be reproducible from specifications.

59. *A secondary standard* is one calibrated by comparison with a primary standard. The use of the term may also be extended to include standards

which have not been directly measured against the primary standards, but derive their assigned values indirectly from the primary standards.

(Because of the lack of a satisfactory primary standard of light, the unit is actually maintained in most laboratories by electric incandescent lamps serving as reference standards. The values assigned to these standards were originally agreed upon as representing the average value of the accepted primary standard as nearly as this could be determined. This procedure is formally recognized in France and the United States.)

60. *A working standard* is any standardized luminous source for daily use in photometry.

61. *A comparison lamp* is a lamp of constant but not necessarily known candle power, against which a working standard and test lamps are successively compared in a photometer.

62. *A test lamp*, in a photometer, is a lamp to be tested.

63. *A performance curve* is a curve representing the behavior of a lamp in any particular (candle power, consumption, etc.) at different periods during its life.

64. *A characteristic curve* is a curve expressing a relation between two variable properties of a luminous source, as candle power and volts, candle power and rate of fuel consumption, etc.

65. *A horizontal distribution curve* is a polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

66. *A vertical distribution curve* is a polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an average vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis, and measuring the average intensities at the different elevations. It is recommended that, in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 deg. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

67. *The mean horizontal candle power* of a lamp is the average candle powe in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

68. *The mean spherical candle power* of a lamp is the average candle power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp in lumens divided by 4π.

69. *The mean hemispherical candle power* of a lamp (upper or lower) is the average candle power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp in that hemisphere divided by 2π.

70. *The mean zonal candle power* of a lamp is the average candle power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone divided by the solid angle of the zone.

71. *The spherical reduction factor* of a lamp is the ratio of the mean spherical to the mean horizontal candle power of the lamp.

(In the case of a uniform point source this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.)

72. *Photometric Tests.*—The results of photometric tests should not be stated in candle power unless the measurements are made at such a distance from the source of light that the latter may be regarded as practically a point. When measurements of lamps with reflectors, or other accessories, are made at distances such that the inverse square law does not apply, the results should always be given as "apparent candle power" at the distance employed, which distance should always be specifically stated. For ordinary illuminants with shades or reflectors a distance of 3 m. (10 ft.) is recommended.

73. *The apparent candle power* of an extended source of light is the candle power of a point source of light which would produce the same illumination at the distance employed.

74. *Photometric Units, Symbols, and Abbreviations.*

TABLE 17

Photometric quantity	Name of unit	Symbols and equations	Abbreviation of unit
1. Radiant flux	Erg per second, watt	I	
2. Luminous flux	Lumen	$F.\ \psi$	l.
3. Luminous intensity	Candle	$I=\frac{dF}{d\omega},\ \Gamma=\frac{d\psi}{d\omega}$	c.p.
4. Illumination	Phot, foot-candle, lux	$E=\frac{dF}{dS}$	ph. f.-c.
5. Exposure	Phot-second, microphot-second	Et	ph.-s. μph.-s.
6. Brightness	Candle per square centimeter, candle per square inch, lambert, millilambert	$b_1=\frac{dI}{dS\cos\theta}$	L. mL.
7. Visibility		$K_\lambda=\frac{F_\lambda}{\phi_\lambda}$	
8. Reflection factor		ρ	
9. Absorption factor		α	
10. Transmission factor		τ	
11. Mean spherical candle power		s.c.p.	
12. Mean lower hemispherical candle power		l.c.p.	

TABLE 17.—*Continued*

13. Mean upper hemispherical candle power	u.c.p.
14. Mean zonal candle power	z.c.p.
15. Mean horizontal candle power	m.h.c.p.

16. A source of unit spherical candle power emits 12.57 lumens.
17. 1 lumen is emitted by a source whose candle power is 0.07958.
18. 1 lux = 1 lumen incident per square meter = 0.0001 phot = 0.1 milliphot.
19. 1 phot = 1 lumen incident per square centimeter = 10,000 lux = 1,000 milliphots = 1,000,000 microphots.
20. 1 milliphot = 0.001 phot = 0.929 foot-candle.
21. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphots = 10.76 lux.
22. 1 lambert = 0.3183 candle per square centimeter = 2.054 candles per square inch.
23. 1 candle per square centimeter = 3.1416 lamberts.
24. 1 candle per square inch = 0.487 lambert = 487 millilamberts.
25. A perfectly diffusing surface of 1 millilambert brightness emits 0.929 lumens per square foot.

Alternative Symbols.—In view of the fact that the symbols heretofore proposed by this committee conflict in some cases with symbols adopted for electric units by the International Electrotechnical Commission, it is proposed that where the possibility of any confusion exists in the use of electrical and photometrical symbols an alternative system of symbols for photometrical quantities should be employed. These should be derived exclusively from the Greek alphabet, for instance:

Luminous intensity	Γ
Luminous flux	Ψ
Illumination	β

CHAPTER V

THE PRINCIPLES OF PHOTOMETRY AND TYPES OF PHOTOMETERS

In measuring the luminous intensity of a source of light the standard of candle power is the fundamental feature and its reliability is of great importance. Having a reliable light standard, the next important feature is the photometer. A photometer is an apparatus for comparing illumination intensities.

All elementary photometry is based on the assumption of a point source of light and that the intensity of illumination due to the light from a point source varies inversely as the square of the distance from the source. Although the *law of inverse*

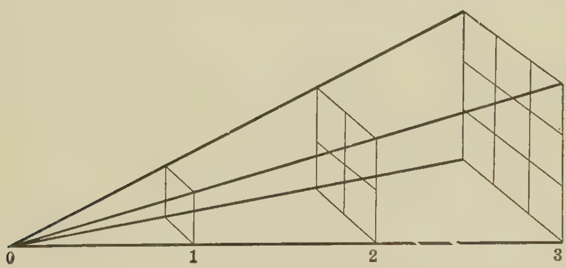


FIG. 32.—Law of inverse squares.

squares is familiar to all students of science and the simple methods of photometry are elements of common knowledge, a brief review at this time may not be out of place. A graphic presentation of this law is shown in Fig. 32, where the source of light is assumed to be at 0 and the rays emitted radially in all directions. It will be seen from this figure that the area of the surfaces normal to the point, enclosed by the radial lines, vary as the square of the distance from the source and since the light rays originate at the source the amount of light flux on each surface must be the same. Hence it is obvious that the intensity must vary inversely as the square of the distance from the source.

The question naturally arises as to *how extensively the assumption of a point source will apply.* This subject has been investigated by Dr. Hyde[1] for a tubular source and a flat circular disk. The results tabulated in Table 18 give the per cent error obtained by assuming the source to be a point source, for different distances from the source. The values in the first column are the ratios of the distance from the source at which the measurements are made to the length of the tube or the diameter of the disk.

Table 18

Errors Due to the Assumption of the Inverse-square Law

Ratio of distance from source to the greatest dimension of the source	Per cent. deviation from inverse square law	
	Tubular source, diam. 0.05 of the length	Surface source circular disk
100	±0.00 per cent.	± 0.00 per cent.
50	+0.05 per cent.	− 0.03 per cent.
30	....	− 0.10 per cent.
25	+0.11 per cent.	....
10	+0.20 per cent.	− 0.98 per cent.
5	+0.09 per cent.	− 3.8 per cent.
4	−0.09 per cent.	....
3	....	−10.0 per cent.
2.5	−1.13 per cent.	....
1.0	....	−50.0 per cent.

From these data it will be seen that at a distance of five times the length of a tubular source or ten times the diameter of a circular surface source the light may be considered as emanating from a point, as far as appreciable error from the assumption of the inverse-square law is concerned.

In photometering a lamp, the illumination on one part of the photometer, varying inversely as the square of the distance from the source, is made equal to that on another part received from some source of known candle power. Then, since the illuminations are equal, it is obvious that the candle-power values vary directly as the square of the distances or

$$I_x = I_s \frac{d^2_x}{d^2_s}, \tag{18}$$

[1] *Bull. Bur. Stand.*, vol. 3, p. 81.

where I_x and I_s are the candle-power values, and d_x and d_s are the distances from the screen of the unknown and known sources, respectively.

If the *distance between the standard and the screen* be fixed and the candle power be maintained constant, then $\frac{I_s}{d^2_s}$ becomes constant and

$$I_x = Kd^2_x. \tag{19}$$

If the *scale of the distances* be graduated according to the square of the distances, the above equation becomes

$$I_x = Kr, \tag{20}$$

where r is the reading on the photometer scale.

From the equation $I_x = Kd^2_x$, the value of I_x may be easily *calculated by means of a slide rule* in the following manner: Place the zero of the slide on the value of K on the upper or A scale, place the cross-hair over the value of d on the C scale, then under the cross-hair there will be the value of d^2 on the B scale and the product $Kd^2 = I_x$ on the A scale.

The Photometer.—The photometer in all its modifications consists of a screen and its accessories. The screen either reflects or diffuses the illuminations under comparison and may be observed directly by the eye unaided, or through the agency of some optical train. The light reflected by the screen is always less than the illumination which it receives and may or may not be of the same quality. *Selective absorption* is often utilized whereby reflected light from an appropriately colored surface agrees in color with the compared light. The *sensitiveness of the apparatus* increases with the reflecting power of the screen.

Diffusing screens scatter the light in its transmission through them. They consist of some translucent substance and, like the reflecting screens, reduce the intensity of the light. They may be designed to change the quality of the light by selective absorption. The *sensitiveness of a photometer screen* depends upon its luminous efficiency, which is proportional to the reflecting or transmitting power, as the case may be, of the material of which it is composed. The sensitiveness of the photometer, distinguished from the above, depends upon the least amount of change in light which the observer is able to detect. This amount may vary from one part in 60 for a weak illumination to one part in 120 for an intense illumination.

Types of Photometers.—There are two general types of photometers:

1. The *stationary photometer* which is usually installed in the dark room and is used for making accurate measurements of candle-power values.

2. The *portable photometer*, which is built in a compact, light-weight form and may be easily employed for making candle-power measurements under actual commercial conditions or for making illumination measurements or surveys.

Photometric Devices.—The different photometric devices may conveniently be divided into four classes:

1. Those dependent on *visual acuity*, which measure the light by the ability of the eye to detect objects illuminated by it.

2. Those in which a photometrical balance is obtained by the "*equality of brightness*" of two surfaces, each of which receives light from a different source.

3. Those where the balance is obtained by contrasting the illuminated surfaces and which are known as "*contrast*" photometric devices.

4. The "*flicker photometer*," wherein surfaces lighted by either source are presented to the eye in rapid succession.

The relative merits of these different types of photometrical devices still remain a debatable subject. The choice of any one will many times depend upon conditions under which it is to be used.

Methods of Obtaining a Photometrical Balance.—Various methods are employed to obtain the photometrical balance, *i.e.*, to produce equal illumination on both parts of the screen. These methods may be enumerated as given below.

1. *By varying the distances between the sources and the screen:* This may be accomplished by moving the comparison lamp, keeping the position of the screen and the test lamp fixed; by varying the position of the test lamp; or by changing the position of the photometric device relative to the two lamps. Reference to the equations at the beginning of the chapter will indicate that calculations are simplified by having the distance between the standard lamp and the screen fixed. This may be conveniently accomplished in dark-room photometry by rigidly coupling the supports of the standard lamp and the photometric device together and by varying their position relative to the test lamp placed at zero on the photometer bars. Of the different methods

of varying the intensity of illumination on the photometer screen this method is the most universally applicable; it possesses accuracy, reliability, simplicity, flexibility, and can be easily verified.

2. The *absorbing medium* offers a satisfactory and practical means of decreasing the illumination intensity if it be free from selective absorption. It may be used in connection with the variations of distances and in this way increase the range of the apparatus. It may be placed between the screen and the test lamp if large candle-power values are involved, or between the screen and the standard lamp if low illumination intensity on the screen is desired or if the standard is of too high candle power. In this case the equation mentioned above involves another constant which will be the transmission coefficient of the absorbing media. If the photometer scale is graduated proportional to the square of the distances, Eq. (20) will become

$$I_x = \frac{Kr}{k'} = K'r \tag{21}$$

if the absorbing medium is between the test lamp and the screen, and

$$I_x = k'Kr = K''r \tag{22}$$

if the absorbing material is between the standard lamp and the screen, k' being the transmission coefficient of the absorbing material.

3. The *rotating sectored disk* is one of the most valuable adjuncts in photometrical measurements. The principle of this device as applied to photometry is based on Talbot's law. This law as stated by Helmholtz[1] is as follows:

> If any part of the retina is excited by intermittent light, recurring periodically and regularly in the same way, and if the periods are sufficiently short, a continuous impression will result, which is the same as that which would result if the total amount of light received during each period were uniformly distributed throughout the whole period.

The application of this law to the rotating sectored disk was investigated by Dr. Hyde,[1] who used different colored light and various-size openings in the disk. These investigations verified the law within the limits of experimental error. Dr. Hyde's conclusions were as follows:

[1] *Phil. Mag.*, ser. 3, vol. 5, p. 321.

[1] *Bull. Bur. Stand.*, vol. 2, p. 1.

Talbot's law, in its application to a rotating sectored disk, is verified for white light for all total angular openings between 288 and 10 deg., to within a possible error of 0.3 per cent, which probably expresses the limit of accuracy of the experiments. The observed deviations from the law for red, green, and blue light are of the same order of magnitude as those for white light, and hence Talbot's law is verified for red, green, and blue light, though not to such a high accuracy as for white light. Moreover, a difference in color on the two sides of the photometer screen produces no appreciable change in the observed deviation from the law.

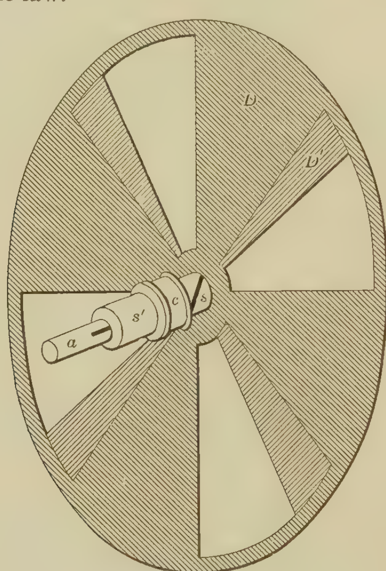


FIG. 33.—The sectored disk.

The disk may be constructed in several forms. The simplest method of obtaining various ranges by means of the disk is obviously to make a set of disks from some thin material, as sheet metal or fiber board, having different-size openings in each. In this way the intensity can be reduced by definite steps from nearly normal value to zero. These different disks may be mounted one at a time on the shaft of a small motor.

It is obvious that a disk, the openings of which could be varied without stopping the motor and changing disks, would be desirable. Such a device is shown in Fig. 33. There are two disks, D and D', which may be moved relative to each other about the same axis. Both are mounted on the same shaft but on separate

sleeves, one sleeve over or outside of the other. By making a spiral slot in one sleeve and a longitudinal slot in the other and by placing a pin through them into the shaft, the size of the openings between the sections of the disks may be easily increased or decreased by sliding the sleeves along the shaft in the proper direction. This change in adjustment may be made while the disk is in operation by placing the end of a lever in the groove of the collar *C* which is attached to the sleeves. The other end of the lever may be placed above a scale calibrated to indicate by the position of the lever the value of the openings in the disk. With this arrangement the intensity can only be varied through a range of about 50 per cent.

The minimum speed of rotation is that at which no flicker effect is experienced. Higher speeds give the same results.

The Bunsen photometer is one of the oldest and simplest forms of photometric devices. Moreover, it is still widely used and constitutes an efficient means of comparing the intensity of luminous sources. The screen differs from those used in the photometers previously described. In its simplest form this screen consists of a sheet of white paper a part of which is made translucent by paraffin or some other similar substance. The transparent portion is usually star-shaped, with its edges sharply defined. The light falling on either side of the screen is partly reflected and partly absorbed, while that falling on the treated part is partly transmitted. If the same per cent is absorbed by both parts of the screen, a greater amount will be reflected from the untreated part. When the illumination on both sides of the screen is the same, an equal amount of light is transmitted through the treated portion in each direction and if the light from each source is of the same hue both sides of the translucent portion of the screen should appear identical. If the same per cent of light be absorbed by both the treated and the untreated portions of the screen, the entire surface of both sides of the screen will then appear identical when a photometrical balance is obtained, provided the color of the light from the two lamps is the same. The coefficient of absorption of the translucent portion is, however, usually greater than that of the untreated part and a contrast is observed when a setting is secured.

Both sides of the screen are viewed simultaneously by means of two mirrors mm' (Fig. 34) properly arranged. It is essential that the mirrors have the same reflecting power and make the

same angle with the screen. Both sides of the screen are used in obtaining a balance although either or both sides may be used if the absorption of both the treated and the untreated portions be the same. As the screen and the mirrors are reversible, a second balance can be obtained and the mean taken as the result, thus eliminating any error which might arise from dissimilarity in either the sides of the screen or in the mirrors. Referring to the figure, both sides of the screen *ss'* are viewed through the eyepiece *O* by means of the mirrors *mm'*.

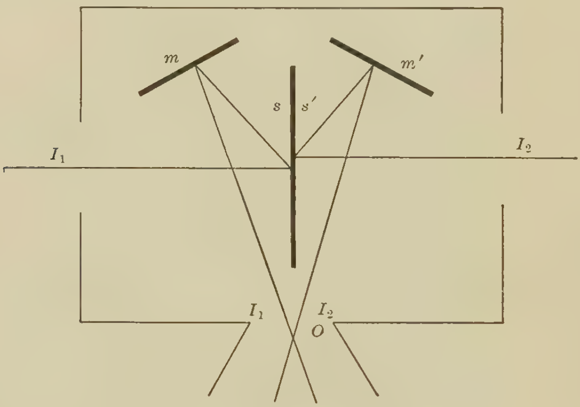


Fig. 34.—The Bunsen photometer.

The Leeson disk is an improvement over the Bunsen disk. It consists of a piece of thin translucent paper with an opaque piece having a central star-shaped opening pasted on either side of it. The edges of the openings exactly coincide on the two sides of the screen. This screen, like the Bunsen, may be of either the contrast or the disappearance type and, since the edges of the translucent portion are more sharply defined than those of the Bunsen, less difficulty is experienced in detecting slight inequalities in the illumination of the two sides of the screen.

The Lummer-Brodhun photometric device consists of a purely optical combination for viewing the two sides of the screen. A diffusing screen *ss'* (Fig. 35) of high reflecting power is placed in, and with its plane normal to, the photometric axis. This screen is viewed on both sides by means of the optical device which presents both sides of the screen to the eye as adjacent or concentric fields.

The Lummer-Brodhun photometer is built both as an "equality-of-brightness" and as a "contrast" photometer. The arrangement of each is essentially the same. The light from the two sources, reflected from the sides of the screen s and s', falls on the mirrors m_1 and m_2 and is reflected along a normal to the

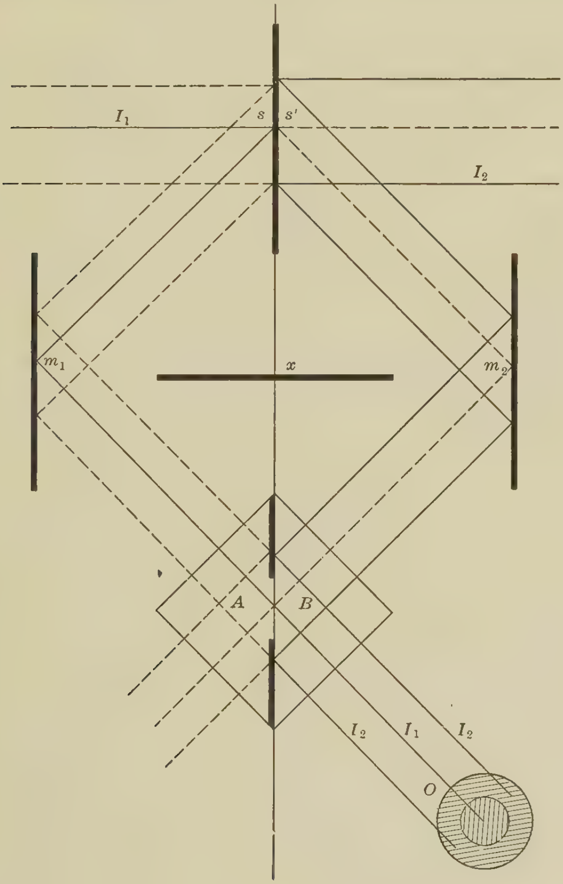


FIG. 35.—The Lummer-Brodhun "equality of brightness" photometer.

surfaces of the triangular prisms A and B. The observer, looking through the telescopic tube O directed normally to B, clearly views a divided field illuminated partly by one source and partly by the other.

In the *equality-of-brightness photometer* the rays from I_1 pass directly through the central part of the prisms illuminating the

central portion of the field as indicated in Fig. 35. The rays from I_2 pass in the same way into the prism B; the central rays pass directly through the prisms while the outer rays are reflected by the prism B and constitute the outer portion of the field of view. The paths of the light rays viewed through the eyepiece

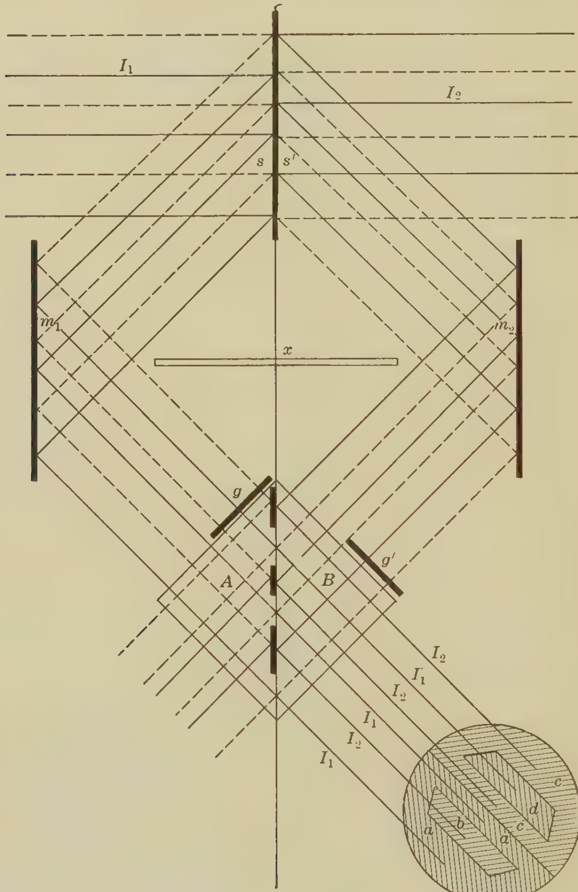


Fig. 36.—The Lummer-Brodhun "contrast" photometer.

are indicated by the full lines. Those shown dotted from I_1 are reflected by the prism A out of the line of vision, while those represented by the dotted line from I_2 pass directly through the prisms out of view. With this arrangement a two-part illuminated field is observed, as shown shaded at O.

In the *contrast photometer* the principle is the same, but the field is divided as illustrated by the shaded part of Fig. 36. The principle can be readily understood from the previous description. It will be seen that the parts of the field a and d are illuminated by the source I_1, while b and c receive light from the source I_2. Two thin pieces of glass g and g' intercept some of the light illuminating the fields b and d, thus giving the contrast effect whereby this photometer receives its name. A photometrical balance is obtained when the intensity of a and c and of b and d are the same; a and c, however, will be brighter than b and d because of the small amount of light absorbed by the two pieces of glass g and g'.

Heterochromatic Photometry.—It has already been shown that the luminous value of a light depends upon its spectral composition, and to some extent upon its intensity. Hence it is obvious that the comparison of the luminous qualities of two lamps differing in color at once becomes complicated. Also it has been found, as might be inferred from previous study of the eye, that a photometrical setting depends upon the size of the retinal area employed or, what amounts to the same thing, the size of the photometrical field.

Sources of light showing but slight color differences can be compared by any of the ordinary methods with an accuracy sufficient for commercial purposes But when comparing lights differing greatly in color it is the general experience that different kinds of photometers give different relative values for colored lights. Even the same photometer used in two different ways, or comparing the lights at two different intensities on the screen, or viewing the screen from different distances may fail to give concordant results. Comparisons repeated on succeeding days by the same observer are likely not to agree with those at first obtained, and, what is still worse, the general conclusions reached by one observer are liable not to concur with those derived by another.

The Flicker Photometer.—The flicker photometer has been designed for comparing lamps emitting light dissimilar in color, by presenting to the eye surfaces illuminated by each light source in rapidly alternating succession. Its principle is based upon the investigations of Rood,[1] who discovered that when two surfaces differing in color are presented to view alternately and in rapid

[1] *Amer. Jour. Sci.*, vol. 46, p. 173.

succession the sensation of color disappears, or the color sensations are combined and the color difference lost, although the sensation of flicker may persist. Rood also found that when these two surfaces were equally illuminated no sensation of flicker was experienced.

Moreover, the rapid alternations—presenting first one and then the other illuminated surface—tend to exercise the eye at its maximum sensitiveness, and so should reduce the personal variable. This seems verified by the results of experiments, which show that this type of apparatus can be used for comparing light sources presenting the widest contrast in color with a consistency approaching that of the ordinary types of photometers when balancing lights of the same color. Such results are obtainable only with the normal eye, the fatigued eye showing a differential sensibility toward one of the lights.

The active part of the retina results in what is sometimes referred to in photometry as the "*yellow-spot effect*," the "yellow spot" or fovea, being the small central region of the retina. It will be remembered that the cones are the predominating light-perceiving organs in this region, and that it is at this point that greatest sensibility is obtained. With this point in mind, together with the other peculiarities of the eye previously discussed, it will not be surprising to find that the readings obtained by photometers when comparing different colored lights may depend, within certain limits, upon the size of the photometrical fields, or, what amounts to the same thing, the distance of those fields from the eye of the observer. Investigations of this nature, obviously involving low intensities, by Mr. Dow[1] show quite appreciable differences in readings due to these causes.

Another disturbing factor in heterochromatic photometry is known as the "*Purkinje effect.*" It appears that the normal eye can distinguish details better in and is more sensitive to light of a greenish or bluish hue when the illumination is of low intensity, while the greenish-yellow hue becomes more efficacious when cone vision comes into prominence and at higher illumination intensities. An investigation of the ratio of ruby-red to signal-green light, two colors distinct enough in color to show the Purkinje phenomenon effectively, by Mr. Dow,[2] shows that this factor becomes negligible at ordinary and high intensities.

[1] *Illum. Eng. London.*, vol. 2, p. 610.

[2] *Elec. World*, vol. 55, p. 465.

The flicker photometer appears to be influenced less by the yellow spot and Purkinje effects than the equality-of-brightness photometer, although it is less sensitive at low intensities. Comparative results showing this as obtained by Mr. Dow are

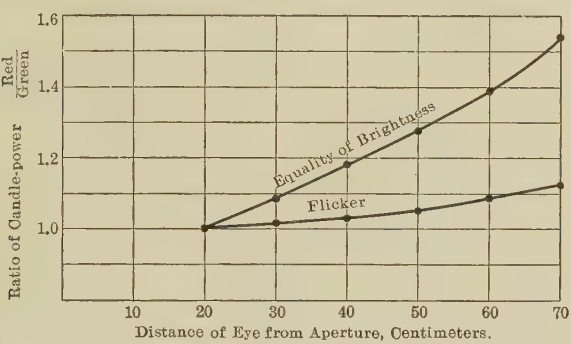


FIG. 37.—Comparison of "yellow spot effect" in flicker and equality of brightness photometers.

shown diagrammatically in Figs. 37 and 38, where the ratios of the apparent candle power of ruby-red light to signal-green light are given for the two classes of photometers. The wedge arrangement was used. Precautions were taken, for the yellow-

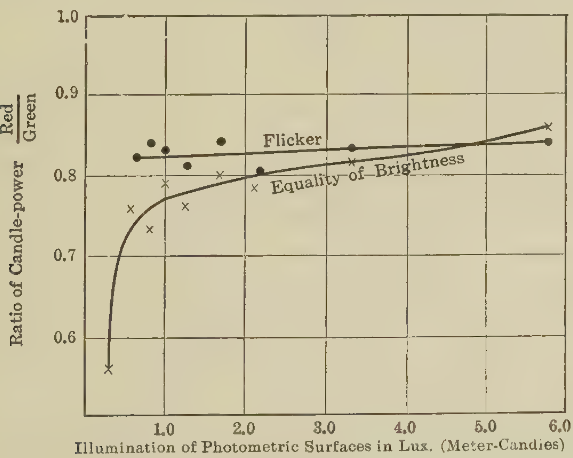


FIG. 38.—Comparison of Purkinje effect for flicker and equality-of-brightness photometer.

spot effect, to insure the use of the same portion of the retina for each instrument at successive distances from the screen. The retinal area, of course, decreased as the distance increased. For

obtaining the results shown in Fig. 37 the intensity on the screen remained constant.

In Fig. 38 a comparatively large retinal area was used to secure greater sensibility and was of the same size for both photometers. It will be seen that with the equality-of-brightness method the values of the red light in terms of the green light become much less as the intensity of illumination is reduced, which is in agreement with the Purkinje effect, but with the flicker arrangement these ratios show no marked variation in value.

These physiological peculiarities arising from the use of the two types of photometers mentioned above have been verified, qualitatively at least, by several investigators. They indicate that, where low intensities of illumination differing in color *must* be compared, the flicker photometer will yield results less influenced by the yellow-spot and Purkinje effects than will the equality-of-brightness type of photometric apparatus.

The discrepancies in results obtained by different observers when different colored lights have been compared at high intensities have often been attributed to the Purkinje and yellow-spot effects, but it has been proved quite conclusively that these disturbing influences occur only at low intensities.

Dr. Bell[1] has shown that errors in heterochromatic work, with the equality-of-brightness photometer and at intensities above the range of Purkinje effect, are the direct effect of *simultaneous contrast* which modifies the apparent luminosities of two colored lights under comparison. When red and green, for example, are in juxtaposition, the red appears redder and the green greener to a very noticeable degree if the circumstances are favorable. According to Titchener,[2] the increase in this contrast effect is always in the direction of the greatest opposition in colors. It increases with the saturation of the more prominent color and is always greatest when there is no simultaneous brightness contrast. The contrast is also sharper if the two colored surfaces are very close, and not separated by visible boundary lines.

The *effect of simultaneous contrast* may be seen by placing a greenish light source, a mercury arc, for instance, on one end of the photometer bars on which is mounted a Lummer-Brodhun screen. When observed through the eyepiece the field appears a faint bluish-white similar to the color of the tube. If the

[1] *Elec. World*, vol. 59, p. 201.

[2] "A Text-book of Psychology," p. 76.

mercury lamp is extinguished and the other side of the screen illuminated by a carbon lamp, the field will appear the usual yellowish-white. But if both lamps are lighted, the sides of the screen become at once a conspicuous green and a brilliant orange, neither in the least resembling the color when either was used by itself. Hence it will be seen that due to contrast two colors in juxtaposition may be changed in hue to a surprising degree and abnormally thrown apart in the spectrum. Dr. Bell[1] suggests Fig. 39 as conveying an approximate idea of what happens in such a case. Suppose two lights of the spectral regions a and b are being compared. When thrown on the screen in juxtaposition the hues are changed by contrast so that the red becomes redder

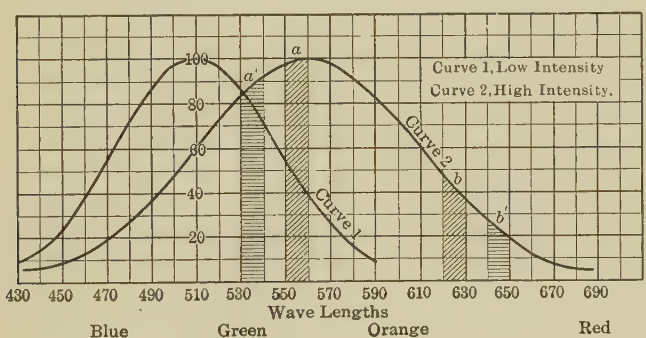


FIG. 39.—Luminosity at high and low intensities.

and the green greener. The contrasts therefore correspond to colors of lessened luminosity, but lessened in unequal degrees, as, for instance, a shifting to a' and b to b'. The red is relatively more decreased and a photometrical balance based on the contrast values would show an apparent Purkinje effect at illumination intensities much higher than those within which the real Purkinje effect comes into play.

As illumination intensities are greatly increased, even spectral colors become relatively less saturated and would consequently affect each other less by simultaneous contrast. As the lower limit of color vision is approached, on the other hand, the effects of contrast are less conspicuous, so there would be a gradual transition into the actual Purkinje effect when the intensity is reached at which rod vision is dominant.

[1] *Op. cit.*

In ordinary illuminants the red side of the luminosity curve is somewhat steeper; hence an equal shifting of two contrasting colors would be of the nature explained above. In view of these conditions it is probable that a large proportion of the aberrances found between different observers, and by the same observer at different times when using the equality-of-brightness photometers, are mainly due to the phenomena here described.

The flicker photometer eliminates simultaneous contrast. The color flicker disappears before the brightness flicker and when the balance is actually determined by the disappearance of the latter the colors have blended into a combination of the two from which simultaneous contrast has disappeared.

Color difficulties can also be reduced in the Bunsen or Leeson screens by making the central portion of the field of such thin, translucent material that there will be a marked color blending there, which will greatly reduce the color contrast.

The concluding paragraph of Dr. Bell's article[1] is given below and sums up the question of the choice of photometer for color photometry as far as color contrast is concerned.

> In making a judgment of brightness such as has to be made in an equality-of-brightness photometer the eye can depend only on what it sees and therefore makes its judgment on the apparent colors which it sees as influenced by contrast. Hence, if the contrast is of such a character as to shift the effective luminosities of the two color fields by unequal amounts, a color error will be introduced in the setting, and since the red side of the luminosity curve is usually steeper than the green side, the net result in comparing colors is often to produce a spurious Purkinje phenomenon perceptible even at fairly high illuminations. Even when this effect does not exist, the shifting of colors by contrast along the luminosity curve still takes place, and since different observers and the same observer at different times vary in preception of simultaneous contrast, small and shifting color errors are constantly introduced in photometric observations which bear no relation to the genuine Purkinje phenomenon or to the absolute color sense of the individual observer. Perhaps the strongest claim of the flicker photometer rests on its freedom from errors of this kind, due to the fact that color blending is secured at a lower frequency than corresponds to the disappearance of brightness flicker, and in fact the flicker photometer is the only form in which simultaneous contrast is fully eliminated, which is another good reason for employing it in heterochromatic comparisons.

[1] *Op. cit.*

A series of researches by Dr. Ives[1] are of great value in solving the problems in heterochromatic photometry. In these investigations Dr. Ives used the flicker and equality-of-brightness arrangements for obtaining the luminosity curves showing the comparison of the spectral colors with white light. The apparatus was so designed that it could be used for both the equality-of-brightness and the flicker methods without disturbing any of the critical conditions.

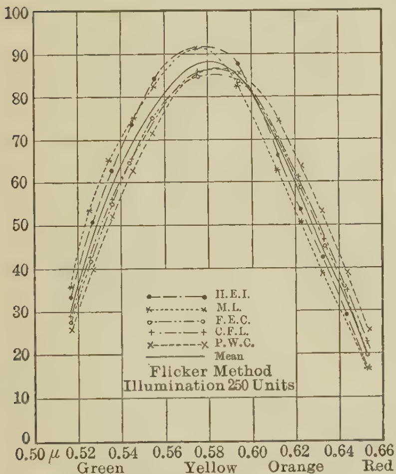


FIG. 40.—Relative luminosity of monochromatic light (flicker method).

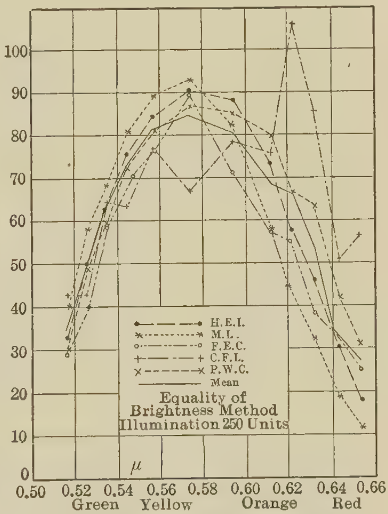


FIG. 41.—Relative luminosity of monochromatic light (equality of brightness method).

The two illuminations used were 10 and 250 units, where a unit is the illumination of 1 meter-candle on a surface of magnesium oxide as viewed through an artificial pupil of 1-sq. mm. area. Because of the small area of this pupil opening, the effective illumination was probably about one-tenth of these values. A circular photometrical field 16 mm. in diameter at 24 cm. from the eye was chosen. This field subtended an angle of 4.5 deg., approximately the size of the yellow spot of the retina.

Readings were taken with each type of photometer for twelve points in the spectrum, alternately on the red and on the green sides. The average readings of five observers at the high intensity of 250 units are shown by the curves of Figs. 40 and 41. It will be seen that the average of the readings of the five observers, shown

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 711.

by the full lines, are practically coincident for the two types of photometers. It will be seen, however, that there is considerable variation among the different observers when using the equality-of-brightness type. It should be remembered here that the different colors were being compared with white, thus giving a less degree of contrast than the cases previously cited, and also the two fields were not in exact juxtaposition. At low intensities (10 units) the luminosity curves obtained by the equality-of-brightness method shifted toward the blue end of the spectrum according to the Purkinje effect, whereas the luminosity curves obtained by means of the flicker device shifted toward the red end of the spectrum, this latter result being hitherto unobserved. The conclusion drawn from this investigation is that the flicker photometer should not be used for comparing low intensities, as the results so obtained must necessarily be incorrect. For comparing high intensities it may be expected that the results obtained by the two methods may possess approximately the same degree of accuracy. At high intensity it was found that the flicker arrangement showed far greater sensibility and there were less variations in the readings of different observers. These points of merit, together with the greater ease of obtaining a photometrical setting and the less liability of change of the observer's criterion, point to a decided superiority of the flicker photometer for heterochromatic photometry.

Heterochromatic photometry is still a debatable subject, however, and these investigations may be considered as preliminary steps in the solution of the problem as a whole. Quoting Dr. Ives in the paper referred to above where, in referring to the general coincidence of the luminosity curves obtained by the two methods at high intensity, he states:

> This then would be an argument for choosing such an illumination as the standard one for making the heterochromatic comparisons necessary for the preparation of standards of different colors. For it must be clearly borne in mind that such comparisons can, from the nature of vision, hold exactly for only one illumination and size of field. The best solution to be hoped for must contain specifications of these two conditions. When the stage has been reached where one can give a definite candle-power rating to a colored illuminant for a certain illumination the first step will have been made. The second step will be when one can state also what the illuminant's candle power will be at any other illumination, knowing it at the standard.

The Whitman Flicker Photometer.—One of the earliest flicker photometers was made by Whitman. Its construction is illustrated in Fig. 42. The disk *BD*, constructed as shown at the left, revolves around its axis *A*. When in the position shown at the right it presents to the eye of the observer at *O* a surface illuminated by I_1. When *B* has turned from a position in front of the eyepiece the observer sees the surface *C*, which is illuminated by light from I_2. In this way, by rotating the disk *BD* at its proper speed by means of a small motor or similar device, the two illuminated surfaces are presented to the eye in rapidly alternating

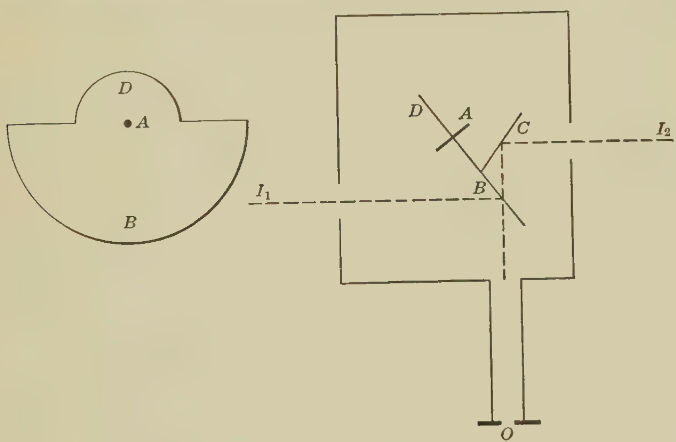


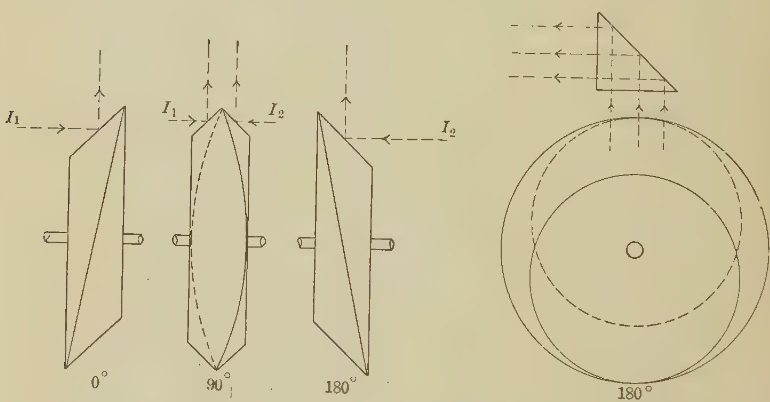
FIG. 42.—The Whitman flicker photometer.

succession, and a balance is obtained by varying the intensity on one surface or the other, as in the ordinary type of photometer head.

The Simmance-Abady flicker photometer consists essentially of a thick disk of plaster of paris driven by a clockwork mechanism. The edges of the disk are beveled as shown in Fig. 43 and these beveled surfaces are viewed from above as they revolve by means of a 45-deg. mirror or prism and the sight tube as shown in Fig. 44. It will be seen from the construction of the disks that the observer sees first a surface illuminated by one lamp and then a surface illuminated by the other, presented alternately and in rapid succession when viewing the disk through the sight tube and the prism. The speed of the disk can be adjusted by a regulator until highest sensibility is obtained. This adjustment is simple and offers no difficulty. One form of this instrument is

so constructed that it can be tilted and lamps photometered at various vertical angles.

The Speed of a Flicker Photometer.—In practice, little difficulty is experienced in obtaining the proper speed of the flicker photometer. This speed should be the minimum at which flicker can be made to disappear when a balance is obtained. In other words, the proper speed is that at which a flicker is most perceptible in a slight unbalancing, but imperceptible when a balance is secured.



Section in the photometric axis. Section normal to the photometric axis.

FIGS. 43 and 44.—The Simmance-Abady flicker photometer.

The Precision Photometer.—Where candle-power measurements of the *highest possible accuracy* are required, as in obtaining the value of the intensity of lamps to be used for secondary standards, in research work respecting the performance of illuminants, in making measurements likely to become the basis of litigation, or, in fact, in any photometric work where a high degree of accuracy is required, recourse should be made to the dark room and the standard bar photometer. The arrangement of the apparatus and auxiliaries for such measurements is shown in Fig. 45,[1] which represents part of the apparatus used for precision measurements at the Bureau of Standards.

For this class of work, a room with its walls, floors, and ceiling painted a dull black, and from which all stray light is excluded, is desirable, although a room with light-colored walls may be used if the necessary screening of reflected light is provided and

[1] *Bull. Bur. Stand.*, vol. 2, p. 1.

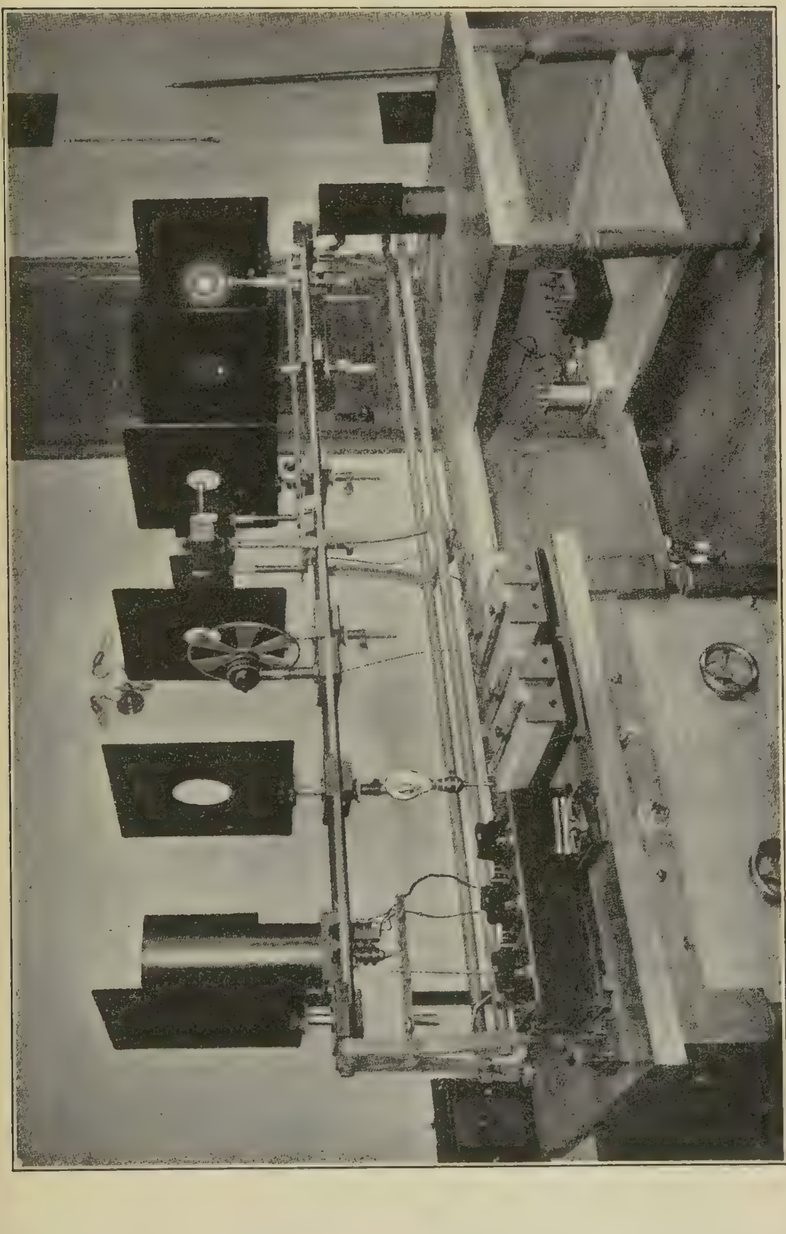


FIG. 45.—A complete photometer bench.

other precautions observed. Having the dark room, the next item is the photometer. This may consist, as shown in the figure, of two bars of tubular or angular cross-section supported on a frame, and the whole device mounted on a bench or table. The standard bars are graduated to read in millimeters and are usually from 2.5 to 4.5 m. in length. These bars support three carriages, two for the lamps and one for the photometric device. These carriages are provided with clamps, by means of which they may be kept in a fixed position, and with holders for the lamps and photometer head. These holders may be raised or lowered to place the centers of the light sources and the screen in the photometric axis and at the same distance above the bars. A carriage carrying a lamp may be placed at either end of the bars and the photometric device moved along the bars to obtain a setting, or one lamp may be placed at the zero end of the bars and the photometer head and the other lamp, with their carriages rigidly connected, moved together. This latter method is more convenient since the equation for calculating the results is thereby simplified. In the figure are shown the rheostats for adjusting the voltage impressed upon the lamps, and at the left the potentiometer for determining the correct value of this voltage. The galvanometer is shown against the wall and the translucent scale, on which a spot of light is thrown by the mirror of the galvanometer, may be seen just back of the potentiometer. A rotating sectored disk may be seen in the photometric axis to the left of the photometer screen.

A series of *screens* are shown, the function of which is to intercept the stray light reflected from the walls and ceiling. Those between the two lamps have openings at their centers and they are so placed that the direct rays from the lamps reach the photometer screen unobstructed. These screens may be made of black velvet or of any material painted a dull black. Unless the material of which the screens are made is very thin, the edges around the holes should be chamfered so as not to reflect light onto the photometer screen. Screens should also be placed so that no light will shine into the eyes of the observer.

Housings are also shown for the two lamps. These, however, are not necessary in a room with dark walls and ceilings, but if used, they should be lined with black velvet or dull-black paint.

Two methods are in vogue for using this apparatus in the photometry of luminous sources, namely, the *direct* and the

substitution methods. In the direct method the standard is placed on one side of the photometer screen and the test lamp on the other, as may be inferred from the above discussion. When a number of lamps are to be tested, it becomes desirable to check the working standards from time to time and the substitution method may be employed. This method may be conveniently carried out by placing the standard lamp at the zero of the scale and the comparison lamp in the carriage attached to the photometer head. After checking the candle power and adjusting the voltage of the comparison lamp, the standard lamp may be removed and the test lamp put in its place. This method will be found convenient when the two sides of the photometer screen are not exactly alike, since it does away with the necessity of reversing the screen and averaging the readings.

CHAPTER VI

PORTABLE PHOTOMETERS AND APPARATUS FOR OBTAINING THE DISTRIBUTION OF LIGHT FROM A LUMINOUS SOURCE

Much attention is being given to the illuminating value of lamps and to the distribution of light from lamps equipped with various types of reflectors. In fact, it is obvious that, in order to predetermine the details of an installation or to compare lamps on the proper basis, data of such a nature become of vital importance.

Various types of portable photometers have been designed and constructed for making illumination measurements, and there are several devices for determining the distribution of light from an equipment. These are discussed on the following pages and a careful study of the use and manipulation of the different types of apparatus should equip the reader with a practical knowledge of this part of the subject.

The principles of portable photometry are essentially the same as those of ordinary photometry discussed in the preceding chapter. They make use of some one of the photometric devices there described, and can, in general, be used for candle-power measurements with possibly a less degree of accuracy. Several methods are employed for obtaining a photometrical balance. Some of these are:

1. Varying the distance between the comparison lamp and the screen.
2. The use of absorbing media.
3. Dispersion lenses.
4. Variable diaphragms.
5. Polarization media.
6. Inclination of the illuminated surface.
7. Variation of the intensity of the comparison lamp.
8. Combinations of two or more of the foregoing methods.

The most accurate and generally satisfactory system of obtaining a balance is the combination of the first and second methods. The *absorbing medium* is used to increase the range of the instrument or to approach a balance by definite known steps, while the *variation of the distance* between the screen and the comparison lamp is used for a gradual approach and for obtaining the final setting.

In making illumination measurements a "*test plate*," consisting of a plain, white surface, is used to receive the illumination to be measured. To give high sensibility to the apparatus, this plate should be made of material having a high coefficient of reflection and should possess a high diffusing quality, so that the intensity received from an angle will obey the cosine law. The plate should be made of material that will not introduce errors due to selective absorption and it should be so placed that neither the instrument nor the observer will intercept any of the light rays which would and should fall upon it. Furthermore, the instrument should be so designed that the test plate can be placed at any angle in a vertical plane passing through its center. The test plate may be of translucent material and viewed from the rear. The same specifications as to freedom from selective absorption and to diffusibility apply also to this type of test plate.

The *ideal photometer* should possess a test plate of plain, white diffusing substance, the most reliable comparison source of light and the best means of varying the intensity of light admitted to the comparison device, thus making a photometrical device of highest sensibility. For making light surveys, and for measuring illumination in general, portability becomes of importance, and a direct-reading scale whereby the values of illumination or candle power, as the case may be, are indicated by the photometrical setting without calculation will be found a great convenience.

The manipulations of a portable photometer for illumination, candle-power, or brightness measurements are discussed in the following pages. Various types of photometers employing the different methods of obtaining a photometrical balance are also described.

A portable photometer extensively used in this country is known as the **Sharp-Millar universal photometer.**[1] This instru-

[1] *Elec. World*, vol. 51, p. 181.

ment represents the endeavor of the inventors to embody in one piece of apparatus the features which characterize the ideal photometer—namely, a sensitive photometric device, the best means of obtaining a photometric balance, adaptability to the use of a reliable source of light for a comparison standard, portability, and simplicity of operation. A further requirement, for the measurement of illumination, is a proper test plate to receive the illumination to be measured. Such a plate should have a surface of sufficient diffusibility so that its illumination varies according to the cosine law, and should be so located that neither the instrument nor the operator will intercept any light which would otherwise fall upon it. With due regard to these features the photometer was constructed as shown in Fig. 46. For a sensitive photometric device a modified form of the Lummer-

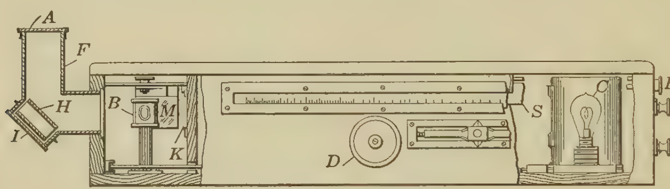


FIG. 46.—Side elevation of Sharp-Millar photometer.

Brodhun arrangement of the comparison-of-brightness type was adopted, and located at B, where it is viewed through a telescopic eyepiece in the side of the box. The *photometrical balance* may be obtained by varying the distance between the comparison lamp and the screen. An electric lamp was chosen for the comparison source, as would naturally be expected, and either a low-voltage lamp of the battery type or one of higher voltage to receive power from the service mains may be employed. When a battery lamp with a tungsten filament is employed, it has been found convenient to use primary cells for the source of power and to maintain the intensity of the standard constant by means of a low-reading ammeter. Then, by the use of lamp cord or similar conductors, the photometer may be used to measure the illumination over a considerable area without having to move the meter and battery. Portability is insured by constructing the body of the instrument of wood and minimizing the number of detachable parts.

A side elevation of the photometer is shown in Fig. 46. The comparison lamp is located at C and can be made to slide along

a track, running lengthwise of the box, by means of a cord which is attached to the supports of the lamp and passes through pulleys and around a drum which is operated by the knob *D*. The light from this lamp falls upon a milk-glass plate at *K*, which is viewed through the optical device. The intensity of light upon this plate is made to vary inversely as the square of the distance from the comparison source by making the inner surface of the instrument a dull black and by interposing a system of moving screens, as shown in Fig. 47. These screens are of fiber, supported on brass rods, and have apertures of sufficient size to permit the direct rays from the lamp to pass unobstructed. At the same time they are of sufficient size to intercept any light reflected from the sides of the box.

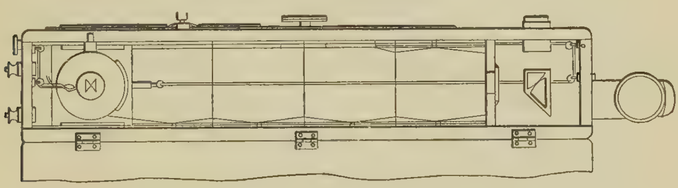


Fig. 47.—Plan of Sharp-Millar photometer.

The scale upon which the indications of the photometer are read is made of translucent celluloid, graduated with an inverse-square scale, and placed in a longitudinal opening in the side of the box. This scale is equipped with a shutter which may be lowered or raised by means of an external knob, and which may be used to exclude external light from the interior of the box. To facilitate taking readings in dark places, a slit is cut in the side of the housing containing the comparison lamp, so that when the shutter is raised the shadow of the pointer, which is inside the box, is cast upon a brightly illuminated scale. On the other side of the housing is a small tube and cross-hair, which, when the comparison lamp is properly placed, throws a line in the middle of a spot of light on the side of the box. In this way the proper position of the lamp is determined.

Beneath the scale and toward the right of Fig. 46 is shown a resistance for varying the current of the lamp. At the rear end of the box are four terminals, two for the supply line and two for the voltmeter, if one is used.

The elbow tube at the end of the box has a number of important functions. It fits friction-tight on a collar fastened in the

end of the box, and hence may be turned about a horizontal axis and set at any angle, which angle is indicated on a semicircular scale on the end of the box. A tube of this description furnishes the simplest means of measuring illumination or light coming from any direction. In the elbow of the tube is fixed a reversible plate, one side being a diffusely reflecting surface used in the measurements of candle power, and the other a mirror used in connection with a test plate on the end of the tube for measuring illumination. In measuring candle power, the diffusely reflecting surface is turned toward the inside of the tube, and the end of the elbow tube is open, the tube serving to screen the plate from stray light. The distance between the plate and the source of light must be known.

The photometer being portable and the elbow tube adjustable to any angle, this arrangement lends itself to determinations of the vertical distribution of luminous intensity of light sources, and is also applicable to the measurement of the candle power of street lamps, either close at hand or at a considerable distance from the lamps.

To measure general illumination, the translucent illumination test plate is slipped onto the end of the tube and the plate at the elbow is reversed, making its mirrored side effective. The illumination on any required plane can then be measured, as the light has unobstructed access to the test plate. It has been found that the test plate of translucent glass, ground on its upper surface so that its power of regular reflection is destroyed, is well adapted to the purpose.

It has been found to be most convenient to make the scale direct-reading in foot-candles. The same scale is equally applicable to the measurement of illumination and of candle power. The foot-candle scale in question has a range from 0.4 to 20 foot-candles. This range can, of course, be increased by the use of absorbing screens. Two such screens are used, one of which transmits substantially 10 per cent of the light falling upon it, while the other transmits only 1 per cent of the light. These two screens are attached to a movable holder, which is shown in detail in Fig. 48. By turning the knurled head, which is exposed when the cover of the photometer box is lifted, either screen may be interposed between the prism and the milk-glass window, or between the prism and the elbow tube, or both screens may be turned to such a position that they intercept no light. Evidently,

when the screens are used, the total range of measurement, with but one comparison lamp, is from 0.004 to 2,000 foot-candles, within which range all measurable lights and illuminations can be said to fall. It is to be understood, of course, that the coefficient of absorption of these screens must be determined exactly by measurement.

To calibrate properly the instrument for the measurement of candle power or illumination, a known candle power or illumination produced by a standard lamp should be employed. The voltage or the current of the comparison lamp is adjusted by means of the slider rheostat on the box to such a value that the pointer on the scale indicates the known candle power or illumination. The instrument then becomes direct-reading for candle power or illumination, as the case may be, all effect of lack of symmetry, etc. being eliminated.

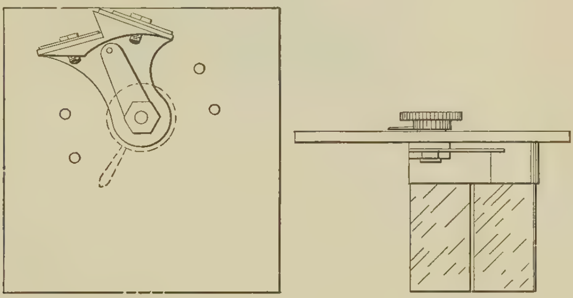


FIG. 48.—Plan of screen system.

The Macbeth Illuminometer.—The photometric principle of this instrument is the same as that of the Sharp-Millar photometer. It has a Lummer-Brodhun-type photometrical device and uses a low-voltage lamp as a comparison lamp. In operation, the comparison lamp is moved back and forth on the optical axis until a balance is observed through the telescope. It has a scale calculated according to the inverse-square law and calibrated to read foot-candles direct.

The Macbeth illuminometer consists of three main parts and various accessories, all contained in a convenient leather carrying case measuring 10 by 17 by 6¾ in. and weighing, complete, 14 lb., with all parts in place except the battery. The battery may weigh from 1½ to 4 lb., depending upon the kind and size of cells used.

The three main parts are the illuminometer, the controller, and the reference standard.

The *illuminometer*, together with the other elements of the equipment, is shown in Fig. 49 and separately in Fig. 50. A Lummer-Brodhun cube is mounted in the rectangular head. By

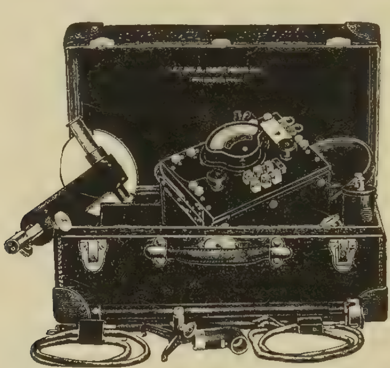


FIG. 49.—The Macbeth illuminometer.

removing the head from the tube and then taking out two screws the cube may be removed for cleaning. It is quite easily replaced, as it is impossible to return it to a wrong position. The photometric field is viewed through the telescope. The aperture opposite the telescope is pointed toward the test plate,

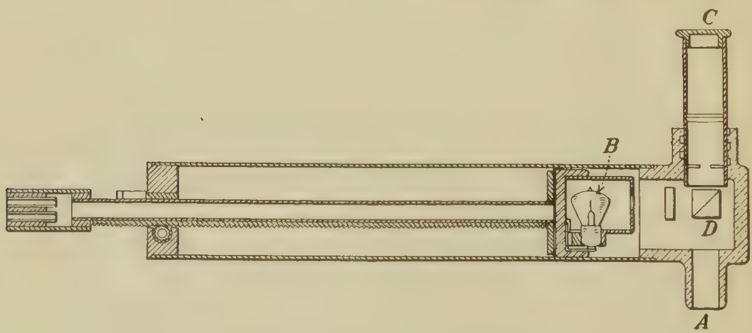


FIG. 50.—Section of Macbeth illuminometer tube.

or any surface the brightness of which is to be measured. In the tube, which is 9 in. long by $1\frac{3}{4}$ in. in diameter, is a diaphragmed carriage within which is mounted an electric incandescent lamp. The lamp carriage is moved up and down in the tube by means of a rack and pinion operating upon a

square brass rod to which the carriage is fastened. This rod is seen projecting from the end of the tube. In this connection it is important to note that the control of the travel of the working standard is positive. All parts involved are metal. On one side of the rod to which the lamp carriage is attached is engraved the direct-reading scale calibrated from 1 to 25 foot-candles. An index point is attached to the bottom of the tube. This index mark is adjustable to allow for variations in filament position of different working-standard lamps. Special attention has been given to the elimination of reflection in the interior of the tube. That this has been successfully done is attested by the fact that the scale follows the inverse-square law. The illuminometer weighs 20 oz.

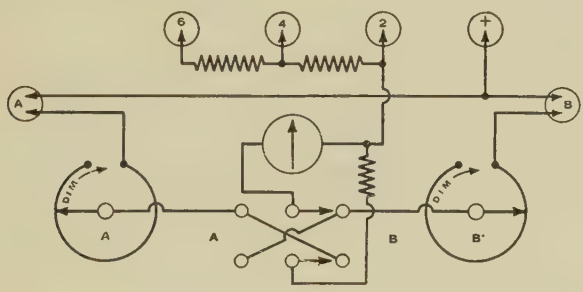


FIG. 51.—Diagram of connections of controller for the Macbeth illuminometer.

The *controller* comprises the battery for operating the lamps, a Weston mil-ammeter, two close regulating rheostats, one for the working-standard and one for the reference standard lamp, and a double-throw switch, by means of which the mil-ammeter may be brought into either the working-standard circuit or the reference standard circuit. The equipment is ordinarily operated from two No. 6 dry cells in series, which may be carried in the leather case and fastened to the under part of the controller. When the mil-ammeter is thrown from one circuit to the other, a resistance is automatically thrown in the circuit from which the mil-ammeter has been removed, this resistance being just equal to the resistance of the mil-ammeter, thus avoiding a change of current through either lamp.

By using a mil-ammeter instead of a voltmeter for the control of the lamps, there is no liability of error due to changes in contact resistances, the breaking of strands in the flexible cords, and other possible sources of difficulty. All flexible cord ends are made up

with set screw connections, so that new cords may be substituted without trouble.

The diagram of connections of the controller is shown in Fig. 51.

The *reference standard* consists of a metal housing, in which is mounted a standardized lamp, fully protected with diaphragm screens. The lamp is seasoned and is run at such low efficiency and for such short times as to insure the greatest possible constancy. The construction of the reference standard is shown in Fig. 52. In using this apparatus it is placed upon the test plate, so that the plate is illuminated by the standardized lamp through the opening *C*. This makes it possible to check the illuminometer at any time or place, making unnecessary a dark room and auxiliary photometrical apparatus. The ease of frequent calibration permits operating the comparison lamp at a much higher efficiency than otherwise, thus securing better color of light and requiring less battery capacity.

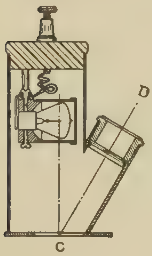


FIG. 52.—Cross-section of reference standard for the Macbeth illuminometer.

In order to increase the range of the illuminometer, absorbing screens of various densities are used. The range with the two screens ordinarily provided is from 0.02 to 1,200 foot-candles,

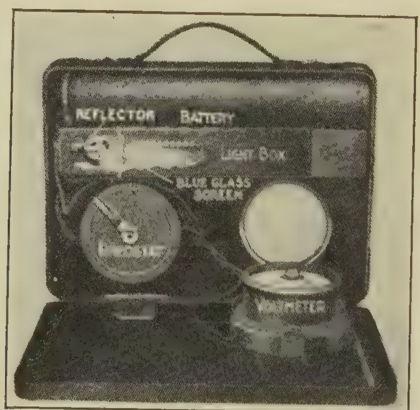


FIG. 53.—Interior view of foot-candle meter.

but this range may obviously be extended by using additional screens.

The test plate is made of white glass finished by a special process to give it good light-diffusing properties.

The foot-candle meter consists of a light box, rheostat, battery, and voltmeter arranged compactly in a small case. It measures approximately 8 by 6 by $1\frac{1}{2}$ in. The light box contains the lamp and screen.

The screen, shown in Fig. 54, consists of a piece of clear glass on which are two thicknesses of paper, the one containing the round holes being fairly opaque, and the other highly translucent. This screen forms one side of the light box, which is so constructed that the screen is illuminated from within to a much higher intensity at the right than at the left. The exposed side of the screen is very nearly uniformly lighted, and the round spots appear brighter than the surrounding screen at the right end and darker at the left. It is evident that, at the point where the spots change from brighter than their background to darker, the illumination on both sides of the screen is approximately

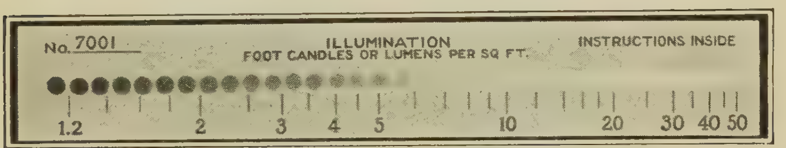


Fig. 54.—Foot-candle meter screen indicating 8 foot candles.

the same. When the instrument has once been calibrated, the illumination intensity on the screen may be read at a glance.

It is obviously important that, after the foot-candle meter has been calibrated, the light supplied to the screen from within be constant for all readings or the indications will be in error. A rheostat, or adjustable resistance, shown in Fig. 53, is connected in series with the lamp and the battery. This permits the voltage applied to the lamp to be maintained at a constant value as the battery gradually depreciates.

The Holophane lightmeter has three principal parts: the photometric head, the lamp and battery with its housing, and the rheostat, switch, and mil-ammeter assembly.

The photometric head is an aluminum case housing a modified Lummer-Brodhun cube.

The standard lamp is a seasoned tungsten-filament lamp rated at 3.8 volts and 0.1 amp. This lamp is operated at approximately 0.05 amp. in order to prolong its useful life. The yellow color of the light, resulting from operating the standard lamp at

reduced current, is compensated for introducing a ground blue-glass screen over the lamp housing, which gives a color which matches the light from a type-C lamp.

A flashlight battery is used, which is located in the battery housing.

The scale reads directly in foot-candles and is engraved on the battery tube.

The direct range of the instrument is from 1 to 15 foot-candles. The photometer head has two slots for inserting absorbing screens, one on the test side and one on the standard-lamp side of the photometric cube. Two absorbing screens are supplied, having transmission factors of 0.1 and 0.01.

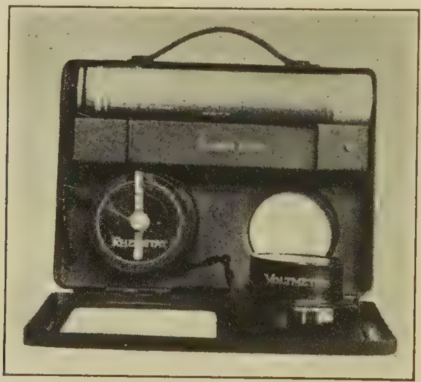


Fig. 55.—The Holophane lightmeter—complete instrument.

The range of the instrument with the two absorbing screens is from 0.01 to 1,500 foot-candles.

A piece of white blotting paper with the mat surface may be used for a test plate.

Compensated Test Plate.—No surface has been found which reflects or transmits light in strict conformity to Lambert's cosine law, *i.e.*, which is of the same brightness when viewed from all angles. The simple test plate supplied with standard photometers is as close an approximation to such a condition as it is practicable to provide. Nevertheless this test plate, like those of other photometers, introduces material error when employed in the measurement of light at grazing incidence. These errors

are very material, amounting to as much as 40 per cent with light incident at 80 deg. to the normal (Fig. 56). Of course, no such errors are encountered in practical illumination measurements, since the component received at such acute angles is not large. Errors of 5 to 10 per cent, however, are frequently experienced as a result of the incorrect rendering of illumination intensities by ordinary test plates. Still greater errors are sometimes encountered in the measurement of street-illumination intensities.

If additional light could be introduced to the plate, so proportioned as to be zero at normal incidence and to increase rapidly

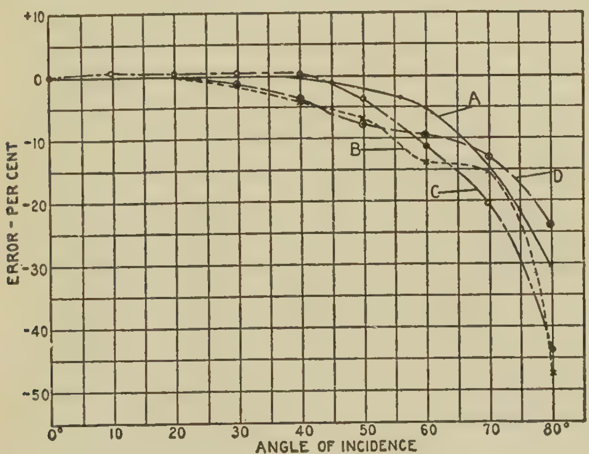


FIG. 56.—Test plate errors. A. Reflection from polished glass, $n = 1.5$, reduced to zero reflection at normal. B. Errors of polished white glass test-plate. C. Errors of polished white glass test-plate. D. Errors of depolished white glass test-plate.

from 50 deg. on, this deficiency might be overcome and the test plate caused to give correct results. It is this idea which underlies the compensated test plate. The construction is very simple. The transmitting test plate, instead of being mounted on the end of a metal tube, is mounted on a little ring of diffusing (opal) glass.

The brightness of the test plate with 0 deg. incidence is not altered by the presence of the opal ring except by internal reflections, but as the incidence increases a larger and larger amount of light falls upon the ring, and by it is diffused in such a way as to add a certain illumination to the under surface of the test plate.

By properly proportioning the transmission of the test plate and the transmission and diffusion of the ring, together with the width of the latter, a compensation for the deficiency in brightness of the test plate at high angles may be obtained.

It is evident that if the arrangement as described were used, light coming at 90 deg. of incidence, which would produce no illumination whatever on the upper side of the plate, would pass through the opal-glass ring and illuminate the under side of the plate. Light coming from angles even greater than 90 deg. might have the same effect. Evidently, this light must be cut off and this is done by the interposition of a saucer-shaped screen with the edge of the saucer in line with the top of the aperture in the

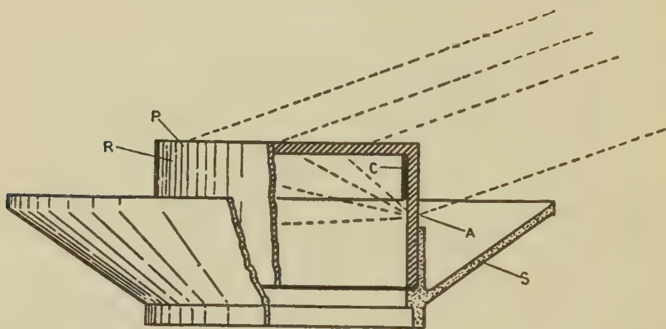


Fig. 57.—Compensated transmitting test-plate. P. Test-plate of polished white glass. R. Ring of opal glass. C. Opaque shield. A. Clear aperture in ring for admission of light. S. Screen to cut off light at 90° incidence.

opal ring. The construction used is shown in half section in Fig. 57 and the actual test plate as attached to a photometer is shown in Fig. 59.

It has been found that if the light is admitted to the opal ring close to the test plate the compensating illumination is not uniformly distributed over the test plate, so that at high angles of incidence the intensity of the field is irregular. Therefore the aperture in the ring is placed well below the test plate. The portion of the opal ring through which light should not pass is covered up by a metal band, the width of which determines the width of the aperture in the compensating ring, and hence the amount of compensating light.

Evidently, the amount of compensating light has to be accurately proportioned to fit the peculiarities of the test plate. If the test plate is quite thin and transparent, a larger amount of com-

pensating light is required than if it is relatively dense. The more perfect the diffusing qualities of the test plate the less compensating light is required. It has been found in practice that the opal ring may be optically quite thin, that is, it may be clear glass with a light flashing of opal. A ring of this character associated with a polished test plate gives a combination which is quite readily adjusted by varying the width of the annular aperture in the ring to conform with the cosine law even at very high angles of incidence.

The construction whereby reflecting test plates may be compensated in accordance with the above-mentioned principles is quite as simple as that of the transmitting test plate. The reflecting test plate proper is made of a disk of depolished white glass; parallel with this disk is placed another similar disk. A

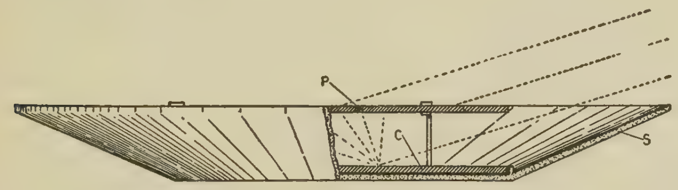


Fig. 58.—Half section of compensated reflecting test-plate. P. Test-plate of depolished white glass. C. Compensating diffuser of depolished white glass. S. Screen for cutting off light at 90°.

similar opaque screen is used for shielding the upper disk from light coming at angles of 90 deg. and greater. Compensation is affected by the light reflected from the lower disk which passes through the upper disk and adds a sufficient amount to the brightness of the test surface. This construction is shown in section in Fig. 58. Here, again, the results of the compensation, while not quite so good as with the reflecting plate, are, for practical purposes, about as good as could be desired. It should be noted, however, that the reflecting plate suffers from the disadvantage that, in order to give these results, the angle of view must be normal to the plate. There does not seem to be any way of obviating this disadvantage. Also, the reflecting plate is considerably more cumbersome than the transmitting plate on account of its dimensions. Evidently, the plate itself must be of sufficient size to cover the entire field of the photometer when the photometer is placed at the desired distance from it. The shading ring surrounding it must be large enough so that it does

not begin to cast a shadow on the lower plate at too small an angle of incidence; otherwise the compensation at high angles of incidence will be incomplete. In the construction investigated the test plate had a diameter of 5 in. and the entire apparatus a diameter of 10 in.

The transmitting compensated test plate is attached to the photometer as illustrated in Fig. 59. The reflecting compensated test plate is a separate device and may be located wherever desired, as, for example, in Fig. 60, where it is employed in the measurement of illumination just over the surface of he street.

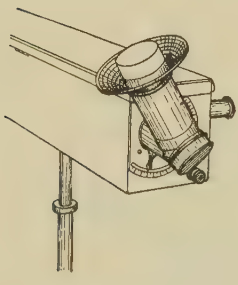


FIG. 59.—Application of test-plate shown in Fig. 57.

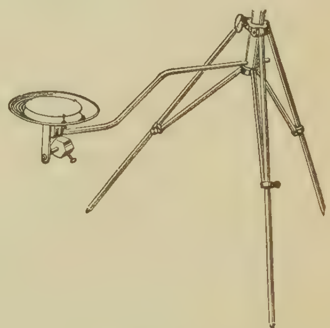


FIG. 60.—Application of test-plate shown in Fig. 58.

Measurement of Coefficient of Reflection.—There are a number of laboratory methods of obtaining this value, some of which employ elaborate apparatus, and take into account with a high degree of accuracy the direction of the incident light, color of incident light, and similar features.

The practical determination of the coefficient of reflection of a diffuse reflecting wall or ceiling is quite simple and can be made by anyone familiar with the operation of a portable photometer employing a detached test plate. The standard on which reflection factors are based is a freshly scraped block of pure magnesium carbonate. One of these standards may be secured at any drug store; a block approximately 4 in. square and 2 in. thick may be purchased for a few cents. The first step in the determination is to scrape the surface of the block and place it in any convenient position relative to an artificial light source. The photometer is then pointed at the block from some angle not far from the normal and a reading taken and recorded. A secondary standard

or working standard, such as a sheet of blotting paper, is next calibrated. This is substituted for the magnesium block, and with the same illumination incident on it as when the previous reading was taken a second reading is taken and recorded. The following proportion is then applied: Reading A is to 98 per cent as reading B is to the coefficient of reflection of the blotting paper.

Taking care that the blotting paper or secondary standard does not become dirty, it is removed to the room in which the test is desired, placed at a convenient position on the wall or ceiling the reflection factor of which is desired, and with the portable photometer a reading taken of the brightness of the blotting paper with the normal illumination received on the wall incident on the paper. The paper is now removed and a reading taken of the wall surface. The coefficient of reflection of the blotting paper has already been determined and the following proportion applies: Reading on blotting paper is to the coefficient of reflection of blotting paper as reading on wall is to the coefficient of reflection of wall.

If the surface to be tested is polished or has a considerable element of specular reflection, then the determination of the coefficient is more complex, and several readings at different angles should be taken to insure obtaining fair average value.

Illumination Surveys.—Illumination surveys, or measurements of illumination at points on a reference plane, are frequently made to determine the intensity and distribution of the illumination due to a lighting installation. This method is often employed to compare the lighting efficiency of two classes of lighting apparatus. In this latter case too much weight should not be given results so obtained, since, due to absence of glare and to greater diffusion of the light, the system giving the lower average foot-candle intensity may be more effective and more satisfactory.

Foot-candle measurements of illumination are ordinarily taken by holding the screens or the ends of the test tubes of the various instruments in a horizontal position at the place of the work. For general illumination in mills and factories, readings are made at an imaginary plane 3 ft. above the floor, while in offices the plane of the desk tops, 30 in. above the floor, is used.

For special cases such as the lighting of shelving, storage bins, or pictures in art galleries, the foot-candles on a vertical plane are the values which interest the careful investigator. In a railway

coach or library, the illumination on a 45-deg. plane—that in which reading matter is ordinarily held—is the value taken.

All records of illumination tests are much more valuable and comparable if the conditions of the test and the data concerning the surroundings are recorded. Records of mere foot-candle readings, without reference to such influencing factors as voltage, cleanliness of lighting devices, color of interior, etc., tell but half the story.

The following type of form sheet for recording illumination surveys is recommended:

TABLE 19

Test No.........
Sheet No........
Date............

Test Description

Investigation of....................At..................................
Observers...
Time start.........................Time finish.........................

The Tested Fixtures

General type.......................Lamps...............................
Glassware..........................Condition...........................
Holders............................Filament position...................
Spread of lights...................Height (to where)...................
Remarks...

The Room Surroundings

Ceiling height.....................Ceiling, color......................
Walls, color.......................Floor, color........................
Goods displayed....................Colors..............................
General class of service..
Remarks...

Points to be Noted

Apparent illumination..............Light direction.....................
Diffusion..........................Glare...............................
Uniformity.........................Dark spots..........................
Fixture shadows....................Furniture shadows...................
Specular reflections...............Due to..............................
Steadiness.........................Reliability.........................
Color effects......................Contrasts...........................
Ease of cleaning...................Breakage............................
Control of lights...
Special features..

Instruments Used

Photometer.........................Standard lamp.......................
Voltmeters.........................Rheostats...........................
Ammeters...........................Accessories.........................

TABLE 19.—*Continued*

Constants

Standard lamp No.................Volts............Amperes.........
Transmitting coefficient light screen. . Transmitting coefficient dark screen. .
Screen in front of photometer lamp........Scale × Coefficient..........
Screen in front of service lamp..........Scale ÷ Coefficient.............
Surface brightness coefficient..
Candle power per square inch of surface observed. . Scale × Coefficient....
Standard distance for candle-power tests..............................
Apparent candle power of source.......................................

Measurements

Rated voltage of service lamps........Make........Bulb..............
Operating voltage of service lamps............Measured at.............
Current of service lamps (..........units)...........................
Wattage of service lamps (............units)........................
Position of test plane..
Readings corrected to..........volts..........By formula.............

In making tests of this nature it is customary to divide the test area into a number of small equal sections, and to measure the intensity of the illumination at the center of each section. If the room is very large and the lighting units well distributed, it is often sufficient to measure the illumination in a number of

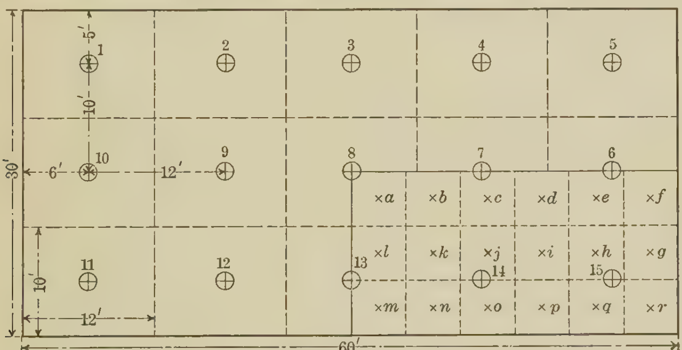


FIG. 61.—Location of test stations for illumination survey.

equal sections of a part of the total area. Assuming that the result of each measurement represents the average intensity of that section, it follows that the average illumination will be the average of these readings. The total light flux in lumens will equal the average intensity in foot-candles multiplied by the area in square feet.

The method of laying off a room into sections for a test as explained above is illustrated in Fig. 61. The fifteen lamps are

located at 1, 2, 3, etc., as shown. It will be seen that the four quarters of the room are similar; consequently, one-fourth of the room may be divided into sections and readings taken at *a*, *b*, *c*, *d*, etc., to obtain the average intensity for the room.

It often happens, when all the light is received from one lamp or cluster and where the class of service makes it impossible to measure the illumination at the proper places, that a certain direction from beneath the source may be chosen, along which the illumination may be measured, and the average intensity calculated from these readings. The locations of test stations

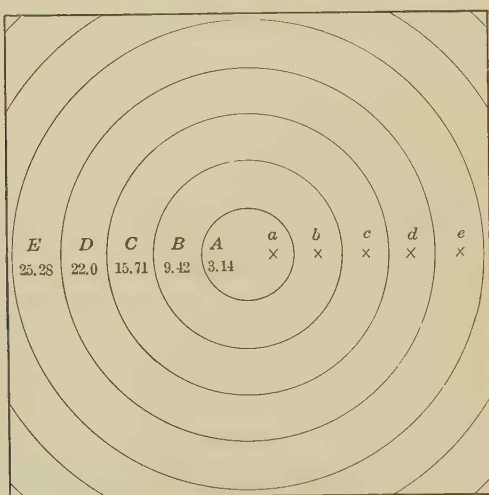


Fig. 62.—Areas and test stations for circular equi-luminous areas.

for a survey of this nature are shown in Fig. 62 by the points *a*, *b*, *c*, *d*, etc. It is essential in a test of this nature that the distribution of light from the source be equal in azimuth and that the reflected light be proportionately distributed; in other words, the measurement at each station should represent the average intensity along the circumference of a circle drawn through that station with the point beneath the source as a center. The representation, interpretation, and calculation of the measurements thus obtained are given on the following pages.

The Representation of Results.—The results of calculations of illumination intensity by the point-by-point method and the values obtained by illuminometry may be presented as numerical values in tabulated form or they may be represented graphically

by curves showing the intensity at different distances from beneath the source or by "equiluminous lines" showing the regions of equal intensity with the value of the intensity given on each line. Still more elaborate methods combining the two just mentioned and showing one or both in perspective or by projection may be employed.

With one lamp the values of illumination intensity may be represented as shown by Fig. 63. These curves represent the distribution of illumination from a 100-watt tungsten lamp when

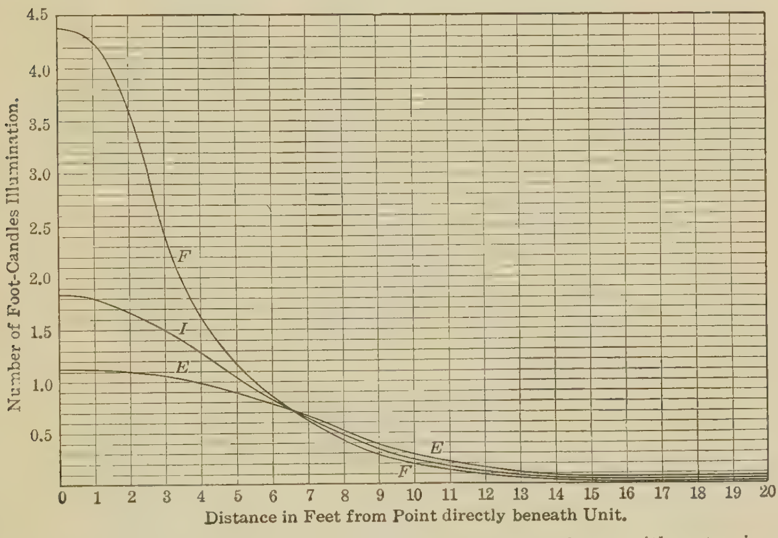


FIG. 63.—Curves showing illumination produced by a lamp with extensive, intensive and focusing types of reflectors. (Lamp eight feet above plane.)

equipped with extensive, intensive, and focusing types of high-efficiency reflectors and when placed 8 ft. above the illuminated plane.

In the same way that the polar curves showing the distribution of light from a source may lead to erroneous impressions regarding the light flux emitted, the illumination diagram of foot-candle values at various distances may also be misinterpreted in regard to the amount of light flux. It should be remembered that these curves represent the intensity at different distances from a point beneath the lamp and that the intensity along a circle with this point as a center and a radius of, say, 4 ft. will be the same as shown at 4 ft. by the curve. If the illuminated area is assumed

to be laid off into a number of concentric circular surfaces, centering beneath the source (Fig. 62), it will be readily understood that, while the intensity may be less at a distance from beneath the source, it is illuminating a greater area and the total light flux may be more than in smaller areas when the intensity is much greater. If such areas are designated by A, B, C, D, etc., each 1 ft. in width, then the area of

$$
\begin{aligned}
A &= \pi 1^2 &&= \pi = &3.14\\
B &= \pi(2^2 - 1^2) &&= 3\pi = &9.42\\
C &= \pi(3^2 - 2^2) &&= 5\pi = &15.71\\
D &= \pi(4^2 - 3^2) &&= 7\pi = &22.00\\
\hline
&&&\text{Total area} = &50.27
\end{aligned}
$$

and if the average illumination intensity of A, B, C, and D be 4, 3, 2, and 1 foot-candles, respectively, then the total flux in lumens is

$$
\begin{aligned}
A &= 3.14 \times 4 = 12.56\\
B &= 9.42 \times 3 = 28.26\\
C &= 15.71 \times 2 = 31.42\\
D &= 22. \quad \times 1 = 22.\\
&\text{Total lumens} = 94.24.
\end{aligned}
$$

Hence the average illumination will be

$$\frac{94.24}{50.27} = 1.87 \text{ foot-candles or lumens per square foot,}$$

and not
$$\frac{4 + 3 + 2 + 1}{4} = 2.5 \text{ foot-candles.}$$

The distribution of illumination from two or more lamps may be represented as shown in Fig. 64. These curves show the intensities along a line connecting points beneath the sources when the lamps are equipped with intensive, extensive, and focusing types of reflectors. In this case the lamps are placed 14 ft. apart and 12 ft. above the illuminated plane.

From a study of these curves it will be seen that more uniform illumination can be obtained by changing the ratio of the distance between the sources to the height of suspension. With the focusing equipment the ratio d/h must be decreased, *i.e.*, the distance between lamps must be decreased or the height of suspension increased. At the same time it is obvious that the intensity of illumination will change, increasing as the lamps are brought nearer and decreasing as they are elevated. By similar reasoning

the other two types must be placed further apart or lower, and the extensive type more than the intensive type.

A satisfactory method of representing the intensity of illumination over certain areas is to lay off the illuminated surface to

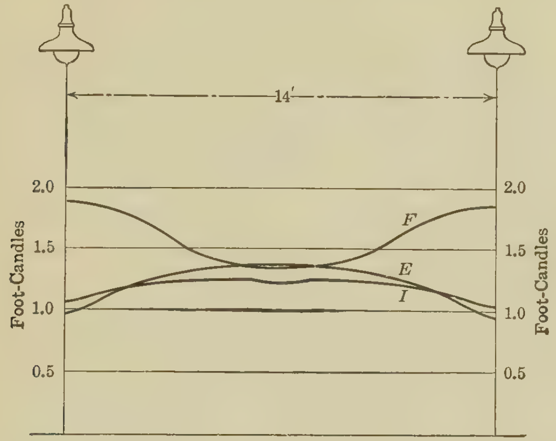


FIG. 64.—Showing illumination due to two units with three types of reflectors. (Lamps spaced 14 feet apart and 12 feet above the floor.)

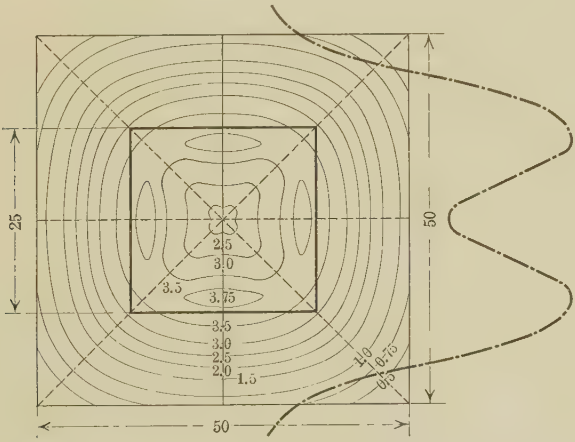


FIG. 65.—Representation of illumination values.

some convenient scale and calculate and plot equiluminous lines. Such a diagram is shown in Fig. 65, which illustrates the distribution of illumination from four sources of rather strong downward intensity placed over the areas receiving the greatest illumination.

The vertical distribution of light through the center of the surface is represented by the broken line at the side of the diagram.

Determination of the Mean Horizontal Intensity of a Source of Light.—There are at the present time several methods for the determination of the so-called mean horizontal intensity of incandescent lamps, *i.e.*, the mean intensity in the plane perpendicular to the axis of the lamp and passing through its center. The oldest of these methods, and one which is equally applicable to other light sources, consists in measuring the intensity at equal angular intervals in the horizontal plane and either taking the mean of these observed values or plotting the observations and determining the mean radius vector of the curve drawn through the plotted points.

A second method is an abbreviation of the first. According to this second method photometric measurements are made in a single fixed direction and the mean horizontal intensity is computed from mean horizontal reduction factors previously determined for each type of lamp. This method is not recommended where accurate results are desired, because of the difference in lamps having a single type of filament. This difference occurs partly in the shape of the filament and partly in the non-uniformity of the glass globe.

A third method, and one which is extensively used in this country in the practical determinations of the mean horizontal intensity of incandescent lamps, consists in spinning the lamp about its axis at a uniform speed of 180 r.p.m. For this purpose a device has been designed having a revolvable socket to which electrical connections are made by means of brushes and collector rings. The socket is supported by an arrangement whereby readings can be taken not only in the horizontal plane but in other directions in a vertical plane through the axis of the lamp with the lamp revolving about its axis. In this way, the mean intensity in different directions in a vertical plane may be determined.

This method possesses two possible sources of error, one caused by the distortions of the filament due to centrifugal force and the other due to flicker, which is perceptible in nearly all types of lamps when rotating at 180 r.p.m. Investigations have shown, however, that at 180 r.p.m. changes in intensity due to centrifugal action lie within the range of experimental error. But with most type of lamps the speed cannot be raised until flicker

disappears without introducing error due to distortion of the filament. The principal source of error[1] appears to be due to flicker and this error differs with different individuals. The conclusion drawn from the investigations cited above is that, where the horizontal distribution curve deviates considerably from a circle so that a bad flicker results when the lamp rotates at 180 r.p.m., some other method for determining the mean horizontal intensity should be employed.

A fourth method of obtaining the mean horizontal intensity of a lamp consists in rotating a pair of mirrors about the lamp which is held in a stationary position. The lamp is mounted with its axis horizontal and coincident with the photometric axis, the tip of the lamp being turned toward the photometer screen. The two mirrors, inclined at approximately 90 deg. to each other, reflect to the photometer screen light emitted from the lamp in a direction perpendicular to its axis. The direct rays from the lamp are prevented from reaching the photometer by a small screen. The mirrors rotate about the axis of the lamp and reflect to the screen a quantity of light proportional to the mean horizontal intensity of the source. This method necessitates, of course, the determination of the reflection coefficients of the mirrors, which is accomplished by means of a standard lamp, the mean horizontal intensity of which has been previously determined by the first method mentioned above.

The arrangement of the rotating-mirror apparatus is shown in Fig. 66. For expermental purposes it was so constructed that the lamp could be rotated independently of the mirrors. The mirrors may be rotated by a motor belted to pulley E. The mirrors are held to the frame by the bolts B and the frame prevented from spreading by the stay rods C. The screen D intercepts the direct rays from the lamp.

It was found that gas-filled lamps, when rotated for the purpose of determining their mean horizontal candle power, changed both in current consumption and in candle power, and that this change varied with the speed of rotation. This change was attributed to the centrifugal force, which caused the cooler portions of the gas in the interior of the bulb to be thrown off to the periphery of the bulb, leaving the filament surrounded by hotter gas than if it were stationary. Hence the temperature

[1] *Bull. Bur. Stand.*, vol. 2, p. 426.

of the filament increased, and with it the candle power and the efficiency of the lamp. It was found further that at low speeds of rotation the candle power of these lamps decreased, so that for every lamp a speed can be found at which the candle power and the watts are the same as when stationary. It was found that the determination of the mean horizontal candle power of gas-filled lamps could be accomplished by rotating the lamp quite slowly at or near this critical speed and placing behind it two

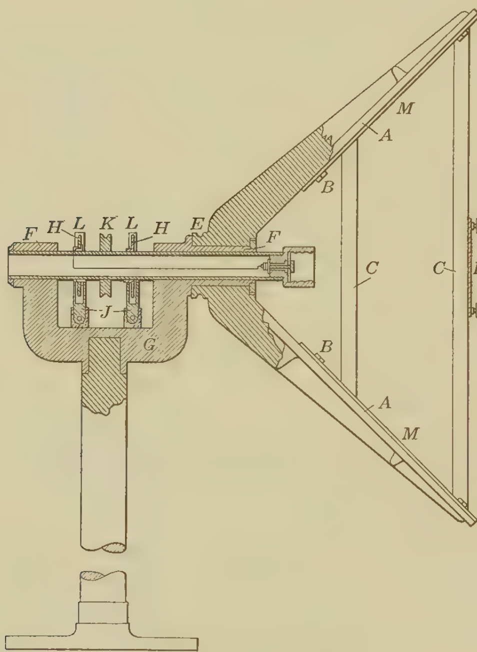


Fig. 66.—Rotating mirrors.

mirrors 120 deg. apart, so that the photometer disk is illuminated not only by the lamp itself but by its two reflected images resulting from beams equally directed about the periphery of the lamp. The two mirrors are employed to obviate the violent flicker on the photometer disk which would otherwise occur.[1]

Apparatus for Obtaining Values for the Polar Curve.—In determining the distribution of light around a lamp which must be burned in a certain position, as, for instance, an arc lamp which cannot be inclined without introducing variations

[1] *Trans. Illum. Eng. Soc.*, vol. 9, p. 1020; *Bull. Bur. Stand.*, vol. 12, p. 589.

in its candle-power values, it becomes necessary to resort to other means than those heretofore described.

A *device for this purpose, consisting of three mirrors A, B,* and *C* revolvable about an axis *D,* is shown in Fig. 67. It will be seen that the beam of light follows a path indicated by the broken

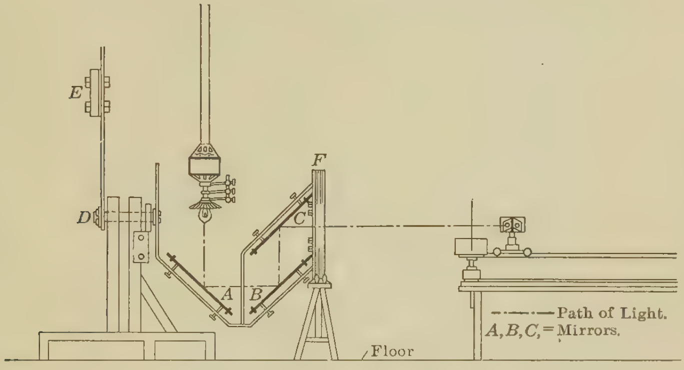


Fig. 67.—Mirror reflector photometer.

line and is compared on the photometric device shown in the right-hand side of the figure. It will be seen that the mirrors can be rotated so as to measure the candle power in a vertical plane. It is obvious that this device can be used for photometering any ordinary source of light and can be calibrated yb

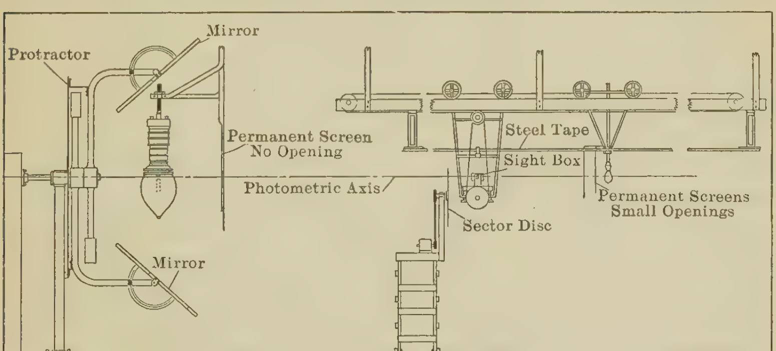


Fig. 68.—Arrangement of twin-mirror photometer.

substituting a source of known candle power in the same way as with the portable photometers.

Another arrangement is shown in Fig. 68.[1] This method embodies many desirable features and deserves more than

[1] *Trans. Illum. Eng. Soc.,* vol. 6, p. 641.

passing notice. It will be seen that the direct rays from the lamp are intercepted by a black screen placed in the photometric axis. The light which is measured is reflected by the mirrors and strikes the photometer screen at an acute angle. This necessitates *calibrating the apparatus,* which may be accomplished either by placing a source of known candle power in the same place as the test lamp, or by removing the intercepting screen and the mirrors and obtaining the constant of the apparatus by comparing the horizontal intensity obtained in this way with the readings obtained when the mirrors were in the horizontal plane and the screen in position. It is obvious that the mirrors are placed as shown merely to illustrate the construction, and when in actual operation each is similarly placed on opposite sides of a vertical line passing through the center of the source of light. Thus if it be desired to determine the candle power 15 deg. below the horizontal a mirror should be placed on opposite sides of the lamp 15 deg. below the horizontal.

Obviously, one mirror can be used instead of two, but two mirrors offer an advantage in arc-lamp photometry by reducing the fluctuations in intensity due to unsteadiness of the arc and the traveling of the arc around the electrodes.

It will be seen from the figure that a *rotating sector disk* driven by a small motor is placed in the photometric axis. This is used to increase the range of the apparatus by decreasing the intensity on that side of the photometric sight box. The sight box and the standard lamp are suspended from a track located above the photometric axis. Reflected light due to the standard lamp is intercepted by opaque screens placed between the standard lamp and the sight box and having openings along the photometric axis large enough to let the direct rays pass through. A photometrical balance may be obtained by changing the size of the openings in the rotating sector disk and varying the distance between the standard lamp and the sight box. The sight box should remain in the same position as when the apparatus is calibrated, so that the incident angle of the light rays will be the same. For very low intensities or with a high candle-power standard the sector disk can be placed on the other side of the sight box. In this way the range of the apparatus can be varied to meet almost any value of intensity.

Still another arrangement for the same purpose, but simpler in construction, is illustrated graphically by Fig. 69. Assume

the source to be located at I and a *test plate A revolvable about the photometr:cal axis mb* to receive the illumination to be measured. The illumination on the test plate A may be viewed through a photometric device placed on the photometric axis and the mirror m located so as to rotate with the test plate. Since the illumination varies inversely as the square of the distance, the candle power can be calculated from the illumination measurements or

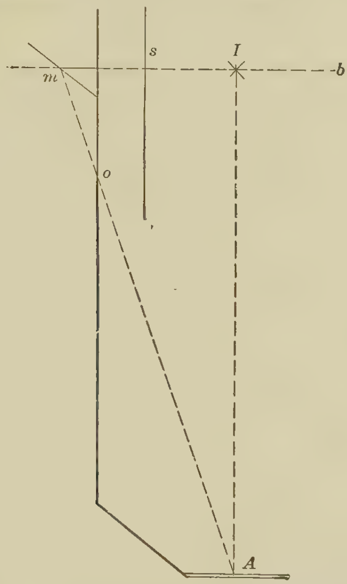


FIG. 69.—Revolvable test-plate for determining the distribution of light.

the device may be calibrated to read the candle-power values directly, in the same way as in the case just described. It is evident that a mirror must be substituted for the screen in the photometric device on the side receiving the light from the test plate. The test plate must, obviously, be far enough from the source that the source may be considered a point source, since the reflection from the test plate will differ from that from a mirror.

CHAPTER VII

LIGHT-FLUX CALCULATIONS AND SPHERICAL PHOTOMETRY

In order to compare luminous sources on the basis of the total amount of light emitted and to be able to determine the amount of light available for illuminating purposes it becomes necessary to understand some of the methods used, and the underlying principles involved, in obtaining the *total amount of light flux emitted*, or any part thereof, by any lighting equipment.

The various methods used in practice for determining the value of the candle power in different directions from the source have been described in the preceding chapter. These values are usually represented graphically by curves plotted to polar coordinates. These curves merely show the distribution of light in one plane (usually the vertical plane) around the source of light as a center. They simply indicate the value of the candle power in definite directions from the source and have no significance as a representation of the quantity of light.

Polar Curves and Spherical Surfaces.—An interesting comparison indicating the misleading conceptions likely to arise in the study of polar diagrams is illustrated by the polar curves of Fig. 70.[1] The four curves *a, b, c,* and *d* represent theoretical distributions of light in a vertical plane. The maximum values in these four cases are approximately in the ratios of 15:19:50:60. However, if these curves represented the distribution of light from luminous sources in a vertical plane, the mean spherical candle power or the *total flux of light would be the same for each.*

The fundamental theory of this section of the subject is based on the study of spherical surfaces, in junction with which it becomes necessary to determine either the mean spherical intensity in candle power or the zonal or total flux of light in lumens. In these spherical calculations it is assumed that the luminous intensity is equal in azimuth and varies only in one plane

[1] *The Armour Eng.*, vol. 3, p. 1.

through the source which, in the following discussion, will be a vertical plane.

If the source of light is assumed to be surrounded by a sphere of radius r with the source as a center, and, further, this sphere is considered to be divided into a number of zones in such a manner that the illumination of similar parts of each zone is uniform, the total flux of light embraced by a zone will be equal to the product of the average intensity and the area of the zone. From a summation of these products for each zone the total value of light flux emitted by the source may be obtained and this divided

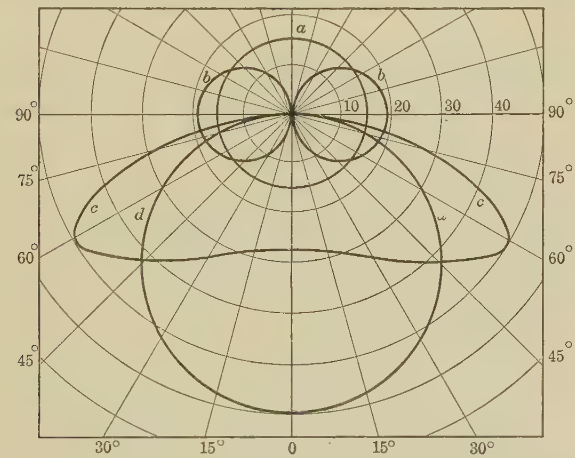


Fig. 70.—Polar curves giving the same amount of light.

by the area of the sphere ($4\pi r^2$) will give the mean spherical candle power.

The light flux in the lower hemisphere will be the sum of the products of the zones and their intensities and this sum divided by the hemispherical area ($2\pi r^2$) will give the mean lower hemispherical candle power.

The area of a zone subtended by an angle embracing the first 15 deg. below the horizontal is 7.66 times as great as the area of the zone extending 15 deg. from the vertical. With the same intensity in each zone, the total flux of light embraced by the former zone will be 7.66 times that passing through the latter. If, now, the source of light is of uniform intensity in all directions and by means of a reflector half of the light from the zone subtended by the first 15 deg. below the horizontal be

redirected downward through the zone extending 15 deg. from the vertical, the intensity in the latter zone will be increased to 4.83 times its former intensity.

These results are shown graphically in Fig. 71, where case I represents the normal condition and the shaded parts the relative amounts of light in the two zones. Case II shows graphically the relative amounts and intensities of light in the same zones obtained by the use of the reflector. Thus the quantity of light depends not only upon the intensities in the different directions, but upon the areas of the zones which the various intensities illuminate.

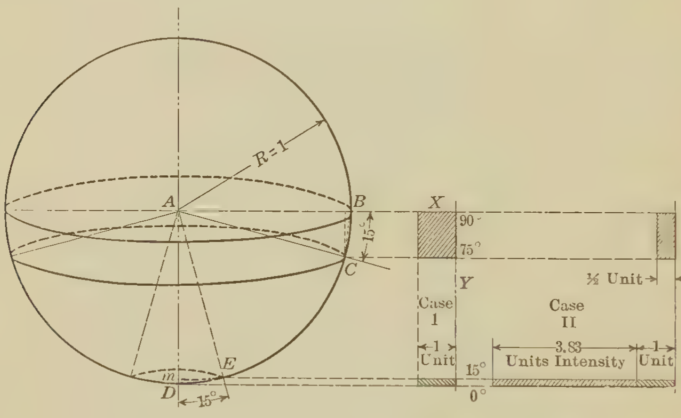


FIG. 71.—Relative areas of zones shown graphically.

It can be shown by spherical trigonometry that the areas of the zones of a sphere are to each other as their altitudes. Thus the luminous flux in any zone of an imaginary sphere surrounding a source of light is proportional to

$$2\pi I(\cos a_1 - \cos a_2), \qquad (23)$$

where $a_1 - a_2$ is the angle subtending the zone of reference, a_1 and a_2 being angles measured from the vertical, and I is the average intensity of illumination in that zone.

This equation forms the basis of the graphic methods of Rousseau, Macbeth, Wohlauer, and others for obtaining the mean spherical candle power and luminous flux in lumens from a source having its distribution of light equal in azimuth.

The Rousseau Diagram.—The Rousseau diagram is the oldest of the various methods by means of which the mean spherical or hemispherical candle power and the luminous flux as a whole

or in part may be obtained. In its construction advantage is taken of the proportionality of the areas of the zones of a sphere to their respective altitudes. The values of the altitudes of zones subtended by equal angles are laid off to scale along the vertical axis of the diagram. These may be determined graphically, as shown in Fig. 72, where the sphere is divided into 15-deg. zones and the zonal boundaries projected on the vertical.

If, on the horizontal lines drawn from the terminals of the successive altitudes, the values of the candle power in the direction of the corresponding angles are laid off to scale, then the area enclosed by the curve, determined by these values of the candle

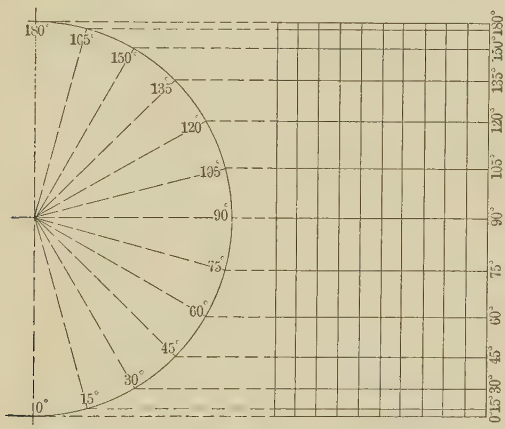


Fig. 72.—Construction of Rousseau diagram.

power at various angles, and the vertical, will represent the total luminous value of the source of light, and the proportional part of the total light in any zone will be clearly shown. The value of this area in terms of the product of the scales to which the curve was plotted divided by the sum of the ordinates or altitudes will give the mean spherical candle power and this value multiplied by 4π will give the flux in lumens. In the same way, areas corresponding to any zone or zones divided by the altitude or altitudes corresponding to the area will give the mean candle power throughout the respective portion of the spherical area. To obtain the value of the mean spherical or mean hemispherical candle power without a planimeter, the area enclosed by the curve may be divided horizontally by twenty lines bisecting areas of equal heights. Without appreciable error the average width of

each section is assumed equal to the distance across the middle of that section. Hence, by reading the lengths of these horizontal lines and by dividing the sum of their values by 20 the approximate value of the mean spherical candle power is obtained. If the hemispherical candle power is desired, consider only the areas corresponding to that hemisphere and divide the sum of the values of the ten lines by 10.

The use of the Rousseau diagram for showing the relative light values of different sources is shown in Fig. 73. The areas

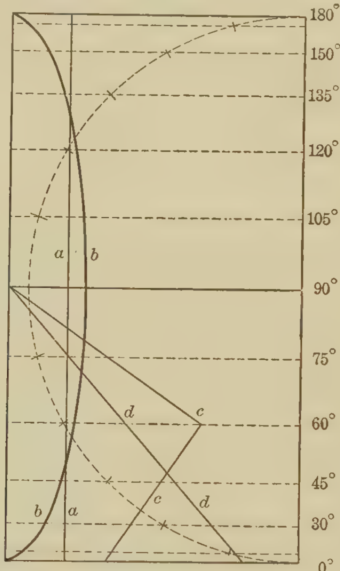


FIG. 73.—The Rousseau diagram applied to curves of Fig. 70.

enclosed between the curves *a*, *b*, *c*, and *d* and the vertical on the left represent the total flux of light from four sources having distribution curves as indicated by *a*, *b*, *c*, and *d*, respectively, of Fig. 70. It will be seen that the four areas determined by the curves *a*, *b*, *c*, and *d* are equal. Since these areas represent graphically to scale the value of the light flux, the result is the same value of the lumens or mean spherical candle power for each.

In the method of determining mean spherical intensities just discussed it will be seen that the spherical area surrounding the source of light was divided into zones of equal areas and the

candle power in the direction of the zonal centers of these areas assumed as the average for that zone.

This method may be applied to any curve plotted on polar coordinate paper as shown in Fig. 74. Choose zones 1, 2, 3, etc. of equal areas (equal altitudes) and draw horizontal lines, *a*, *b*, *c*,

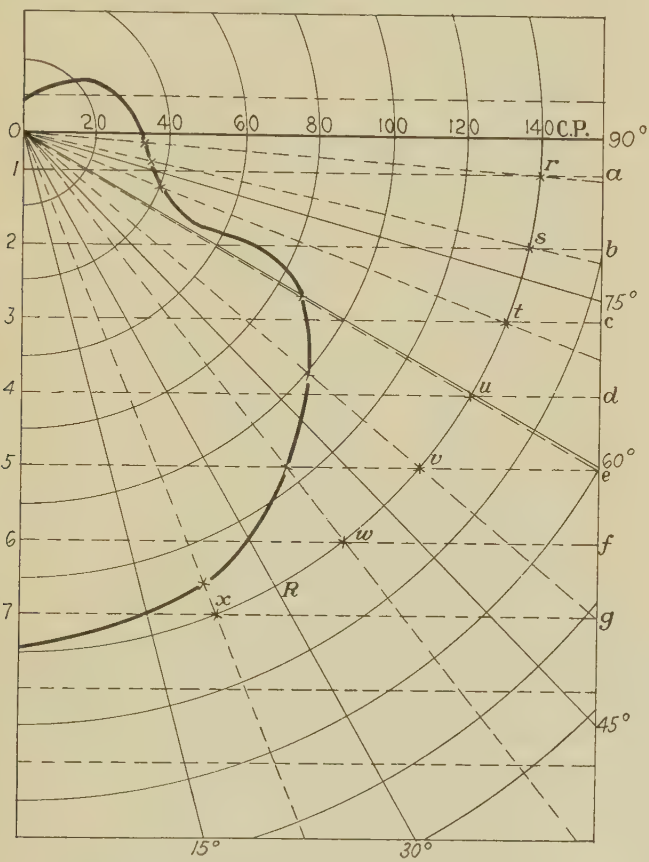


FIG. 74.—Modification of the Rousseau diagram.

etc. through the centers of these zones. If radial lines are drawn from the points *r*, *s*, *t*, etc. where the above horizontal lines cut the large circle *R*, the candle power along these radial lines will represent the candle power in the central parts of the respective zones of equal areas. If the average candle power throughout each zone is assumed to be that of the central portions, then the sum of the candle-power values along the radial zonal lines

divided by the number of lines will give the mean hemispherical candle power.

A more convenient method of applying this method to any polar candle-power curve is to draw the radial lines on transparent celluloid as in Fig. 75, of convenient size to be placed over the polar curves. The values along these lines can be read and the average determined as before.

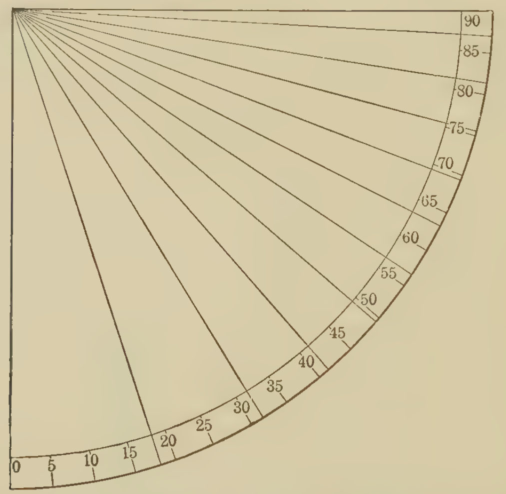


Fig. 75.—Device for obtaining mean hemispherical candle-power.

The "Fluxolite" Paper.—The "fluxolite" diagram[1] devised by Mr. Wohlauer offers a convenient means of determining the luminous flux and spherical candle power. The value of the flux is obtained by simply adding a number of linear dimensions drawn to scale and multiplying the same by some constant. This constant depends for its value upon the number of angular subdivisions of the spherical area.

It can be shown geometrically that the altitude and hence the area of a zone is proportional to the sine of the angle, measured from the vertical axis, which bisects the zone. Hence, if the imaginary spherical area be divided into n numbers of equiangular zones, and assuming the midzone intensity to be the average for the zone, then the flux in any zone will be

$$F = KI \sin a, \tag{24}$$

[1] *Illum. Eng.*, N. Y., vol. 3, p. 655, vol. 4, p. 491, vol. 4, p. 148, vol. 5, p. 132, May, 1910.

where I is the average intensity of the zone, a the bisecting angle measured from the vertical axis, and K a constant the value of which depends upon the number of zonal subdivisions.

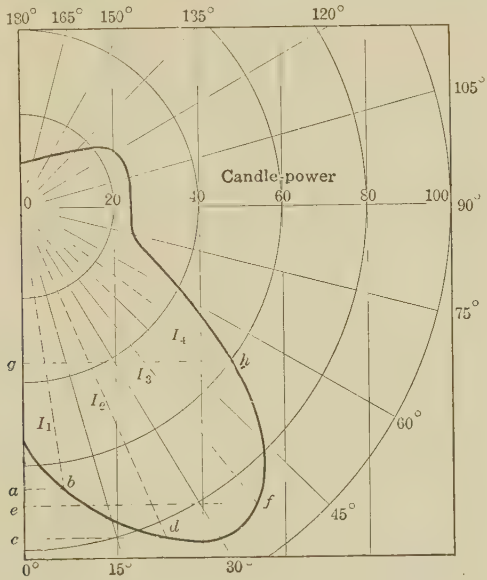


FIG. 76.—Wohlauer's "fluxolite" paper.

Referring to Fig. 76 and representing the flux in successive zones from the nadir by F_1, F_2, etc., the average intensities by I_1, I_2, etc., and the midzone angles by a_1, a_2, etc., then

$$F_1 = KI_1 \sin a_1 = KL_{ab}, \tag{25}$$
$$F_2 = KI_2 \sin a_2 = KL_{cd}, \tag{26}$$
$$F_3 = KI_3 \sin a_3 = KL_{ef}, \tag{27}$$

or

$$F = F_1 + F_2 + \ . \ . \ . \ F_n = K(L_{ab} + L_{cd} + L_{ef} + \ . \ . \ , \text{etc.}), \tag{28}$$

where L_{ab}, L_{cd}, etc. are the horizontal projections of I_1, I_2, etc. Thus the flux in any zone is equal to the horizontal projection of its midzone intensity multiplied by the constant and the total flux in lumens is equal to the sum of the several projections multiplied by the constant.

The mean hemispherical candle power may be obtained by dividing the value of the flux in that hemisphere by 2π, and the mean spherical candle power may be determined by dividing the value of the total flux by 4π. The values of K for various angular subdivisions are given in the following table:

TABLE 20

Constants for Light-flux Calculations

Angular embrace of zone....	5°	10°	15°	20°	25°	30°
Value of K...............	0.548	1.098	1.64	2.18	2.72	3.25

In the example just cited K is equal to 1.64, a being equal to 15 deg.

The polar diagram is constructed with vertical lines spaced equal to the polar scale to facilitate the evaluation of the projections of the various midzone intensities.

By referring to the values of the constants given above it is seen that for zones subtended by 10-deg. angles the value of K is 1.098. If now the polar curve (Fig. 76) was plotted on polar coordinate paper so dimensioned that 1.098 in. would equal some multiple of the candle power, then the lumens could be determined directly by measuring the distances ab, cd, ef, etc. in inches and multiplying by the value of the multiple referred to above.

Modification of Wohlauer's Method.[1]—Still another application of the constant 1.098 conceived by the author is indicated by Fig. 77, where the radial line OK is drawn making an angle XOK (24 deg. 3 min.), the secant of which is 1.098. The spherical surface is divided into 10-deg. zones and the average zonal values of the candle power represented by the radial lines Oa, Ob, etc. If these midzone values be projected vertically onto the line OK and the extremity of each projection be continued around O along the arc of a circle into the horizontal, the value of the flux in lumens in any zone will be represented by the corresponding distance, to the same scale as the polar curve is plotted, along the horizontal OX measured from O. As an example of the manipulation of this method consider the zone between the angles of 40 and 50 deg. from the vertical. Assume Oe, equal to 78, to be

[1] *Elec. Rev. and West Elec.*, vol. 58, p. 440.

the average intensity in this zone. Its projection on OK is equal to Oe' and this value transposed to OX will be Oe'', or 60.5 lumens. In the same way the flux in the 50- to 60-deg. zone will be 77 lumens. By adding the lumens in the different zones, the total lumens in the lower hemisphere may be obtained. The flux in lumens in the upper hemisphere may be found by projecting the midzone values upon the line OK or upon another line 24 deg. 3 min. above the horizontal, and transposing to the horizontal as above.

The simplicity of this method is manifest. The only apparatus necessary is a pencil and a piece of paper and the only calculation is the simple addition of the nine or eighteen values obtained. A

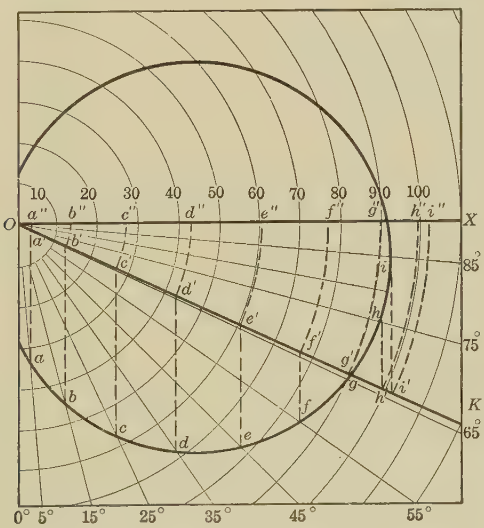


FIG. 77.—Modification of Wohlauer's method.

right-angled triangle will be found useful in securing the projections upon the line OK, but a corner of the sheet of paper on which the curve is plotted may be conveniently substituted.

It is obvious that this method may be applied to any distribution curve plotted upon polar coordinate paper. In this case a series of vertical lines together with the radial line (Fig. 78) laid on a quadrant of transparent celluloid, tracing cloth, or similar transparent material will greatly facilitate operations.

Since the secant of 24 deg. 3 min. is approximately 1.1 (1.098), the midzone values may be projected directly onto the horizontal

line and the sum of the projections multiplied by 1.1, and the same results obtained as above.

The mean hemispherical candle power may be found by dividing the lumens in the hemisphere by 2π (6.28) and the mean spherical candle power by dividing the total light flux of the lamp by 4π (12.56).

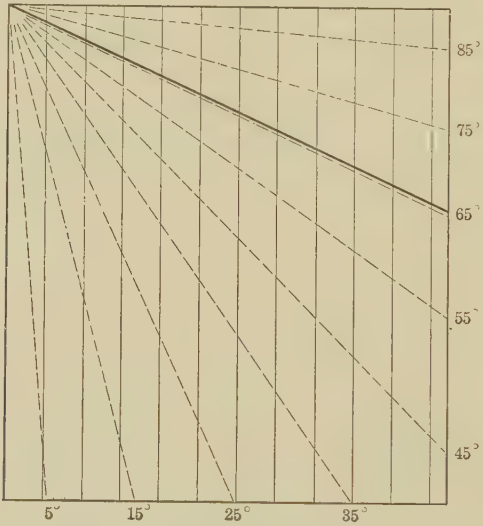


FIG. 78.—Auxiliary diagram applicable to any polar curve.

Spherical Photometers.—It is obvious that where the spherical-light values of a large number of lamps are required and the spherical reduction factor is not accurately known, and especially in the photometry of lamps where the light fluctuates considerably, it is desirable to employ means whereby the result can be obtained by one photometrical setting. This is accomplished very satisfactorily by means of an integrating photometer of either the mirror or the spherical type.

The Matthews Photometer.—The mirror photometer was first designed by Professor Matthews for use in the laboratories of Purdue. By means of it the mean spherical candle power of any source can be determined by one reading, but it is especially intended for arc-light photometry.

In order to produce on the photometer screen an illumination proportional to the mean spherical intensity of the source, it is necessary to direct toward the photometer beams of light from various angles in the vertical plane. It is furthermore essential

that these rays, representing the intensity of light at the respective angles, be reduced in intensity in the ratio of the sine of the angle which the rays make with the vertical, in order that the light from each mirror shall be proportional to the area of the zone which it represents. In developing this method, a ring of twenty-four large trapezoidal mirrors, placed one every 15 deg., surrounds the arc. The inclination of the mirrors to the arc is such that twenty-four images of the lamp are presented to the eye placed at the photometric device. Direct rays from the lamp are intercepted by a black screen. The reduction of the light in the ratio of the sine of the vertical angle is accomplished by

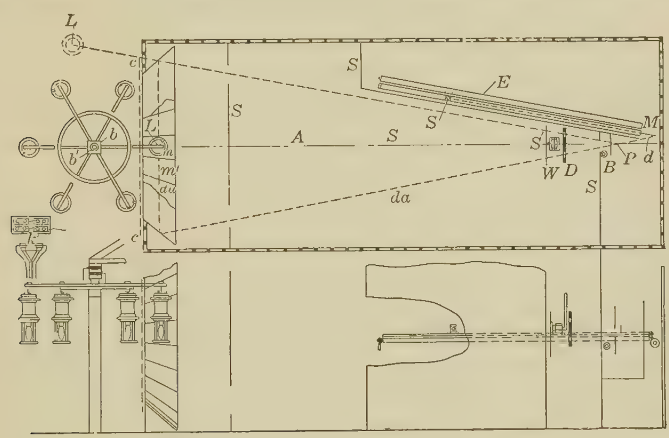


FIG. 79.—The Matthews photometer.

means of a polygonal glass disk composed of as many sectors as there are mirrors and which are smoked sufficiently to give the desired absorption.

One essential condition to the success of this piece of apparatus is that the screen shall receive through each sector only the light from its corresponding mirror. The sector disk can be adjusted by replacing the screen by a cardboard pierced by a small opening and, by sighting through this hole, the disk can be placed with reference to the mirrors. Mirrors of good-quality French plate glass were used and their reflection coefficients were carefully determined for the angle of incidence at which they were used; the maximum difference from the mean value of 0.815 was only ± 2.9 per cent, which was corrected by smoking the corresponding sectors. The smoking of the disks was accom-

plished by burning small quantities of turpentine in a receptacle in which the sector, with a guard ring to insure even density, was placed in a vertical position.

In the photometer described by Professor Matthews, a plan of which is shown in Fig. 79, the light from the standard lamp, because of the small size of the room, was reflected onto the screen by means of another mirror *M*. The illumination on the side of the screen toward the arc lamp, being very intense, was reduced by means of a rotating disk provided with a large number of slots.

The Leonard Photometer.—The Leonard photometer is of more recent design than the Matthews photometer, although similar in theory and construction, the chief difference between the two being that the Leonard photometer has its mirrors located at intervals corresponding to the middle points of successive zones of equal areas. Thus the average of the light thrown upon the screen represents directly the mean spherical or the mean hemispherical candle power, as the case may be, without intervention of smoked sectors.

The globe photometer consists, in part, of a large sphere, with its inner surface painted white. The source of light to be measured is placed inside of this sphere and the illumination at an opening in the surface of this sphere (the direct rays being intercepted by a screen) is proportional to the mean spherical candle power of the lamp. A globe of this kind integrates very successfully the illuminating effect of any source. It involves, in addition, a photometric device and a standard incandescent lamp.

The general theory of the spherical photometer is as follows: When a source of light is placed inside a spherical shell having a matt surface, the light received by any part of the interior surface can be considered in two parts: (1) that coming directly from the lamp, and (2) the light received from the remainder of the interior surface of the sphere after one or more reflections. The quantity (1) is that which is measured in the ordinary photometer which determines the intensity of light emitted in any one direction, and is not considered at all in the globe photometer. According to the theory of the globe photometer, the quantity (2) is constant all over the surface of the shell, and is proportional to the total amount of light emitted by the lamp, quite independent of its position in the shell.

The theoretical argument for this photometer is as follows:[1] Assume a surface P (Fig. 80) to be illuminated by radiation from a small luminous area dA, the brightness of which is B; then the light received on a unit area at P is

$$\frac{BdA \cos a \cos b}{l^2}, \tag{29}$$

a and b being the angles which l makes with the normals to the two surfaces. If now Fig. 80 represents a section through the photometer into which is inserted for measurement a lamp L, indicated in the figure, and the illumination of the surface at the

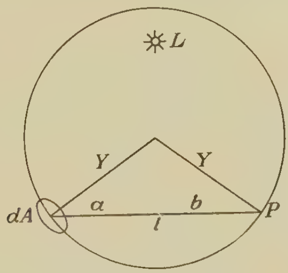


FIG. 80.—Theory of the globe photometer.

point P by light reflected from a small area dA is considered, and the circle shown is a section through the point P and the area dA, then the light received on dA from the lamp directly will be $E_A \cdot dA$, and the $\int E_A \cdot dA = F$, the total light emitted by the lamp. The intensity of dA is $k\,E_A$, since the surface is perfectly matt and throws the light in all directions equally, k being the reflection constant for the surface. The light received from this surface dA at P once reflected is

$$F_A = \frac{kE_A dA \cos^2 a}{l^2} = \frac{kE_A dA}{4r^2}. \tag{30}$$

Hence the illumination at P due to once-reflected light from the whole surface of the sphere will be

$$\frac{k}{4r^2}\int E_A dA = \frac{k}{4r^2}F. \tag{31}$$

It follows at once that the illumination at P by light twice reflected will be

$$\left(\frac{k}{4r^2}\right)^2 F. \tag{32}$$

[1] See also The Hollow Sphere, chap. VIII.

The total illumination at P due to reflected light is

$$F\left(\frac{k}{4r^2} + \left(\frac{k}{4r^2}\right)^2 + \left(\frac{k}{4r^2}\right)^3 + \ . \ . \ . \right) = KF, \qquad (33)$$

where K is the constant of the instrument and depends on the size of the sphere and the quality of the interior surface.

Thus the illumination of the interior of the sphere is theoretically uniform and proportional to the total light emitted by the lamp; therefore, if a small area is screened off from the direct rays of the lamp, the remaining illumination of that area is proportional to the mean spherical candle power of the lamp.

If the lamp be removed to the surface of the sphere so that the center of the source is directly in the surface, then a single measurement will give a value proportional to the mean hemispherical candle power, the ratio of proportionality being one-half that in the determination of the mean spherical candle power.

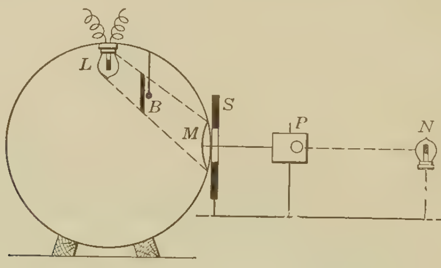


FIG. 81.—The globe photometer.

There are two sources of error in this method; one is likely to occur if the lamp is not in the center of the surface, while the other is due to the non-transparent fittings of the lamp which intercept part of the light. Experiments show that errors due to the latter cause greatly outweigh those due to the former, but that a compromise may be made sufficient for all practical purposes if the lamp is not supported at the center but at a distance of 8 or 15 per cent of the diameter from the top of the inner surface of the sphere, also by making the globe very large.

The construction of this photometer is shown in Fig. 81, where L and N are the two lamps, P the photometric device, S a screen whose aperture can be varied, and M the window of some translucent material protected from the direct rays of the lamp by the screen B.

Experiments with globe photometers give results very consistent with those obtained from "point-to-point" readings, and

tests of a great many different sources of light show that the mean spherical candle power can be obtained by this arrangement with an error of not more than 3 per cent. The apparatus can be calibrated by a lamp of known mean spherical candle power placed at the center of the sphere. The most satisfactory surface for the inner side of the sphere appears to be a coating of lithopone (barium sulphate), and more consistent results are obtained by using a translucent screen of milk glass. This instrument highly recommends itself for the photometry of arc lamps where the distribution of light is not desired, since the fluctuating value of the candle power due to the continual changing of the arc makes arc-lamp photometry, by the ordinary distribution methods, slow and tedious.

The icosahedron represents a modified form of the globe photometer. It is constructed of twenty equilateral triangles, of which fifteen form the body of the apparatus and the remaining five form the door, making its construction easier and more economical. It is some 10 ft. high. In theory and operation, however, it is similar to the globe photometer.

The Kennelly Lumenmeter.—An ingenious arrangement has been designed by Dr. Kennelly for determining the mean spherical intensity or the total luminous flux from a lamp by a single reading. It can be used for the photometry of either incandescent or arc lamps, but when used for the former it has an auxiliary device for rotating the lamp.

It consists essentially of two revolving mirrors and a disk containing a series of openings proportional to the areas of the zones from which the light passing through them comes when the mirrors revolve. The mirrors are placed 180 deg. apart and revolve in a vertical plane about the source of light as a center. The openings in the sectored disk are placed in the paths of the rays reflected by the mirrors onto the photometer screen. The theory of this instrument involves that of the rotating sectored disk and the mirror photometer. It is obviously immaterial with the rotating sectored disk whether the disk rotates and the beam of light is at rest, or *vice versa*. In the mirror photometer the intensity of the light which strikes the sc een from the various zones is made proportional to the light flux in the respective zones. The mirrors of the lumenmeter are driven by a motor and must revolve at sufficient speed so that no flicker is noticeable on the screen.

CHAPTER VIII

PHOTOMETRICAL CALCULATIONS—SURFACE SOURCES[1]

In the previous chapters there was considered the light flux from a source assumed to be a point and illumination and intensity were defined in terms of the flux and candle power, respectively. In this chapter the light distributed over a luminous area of brightness b and the total quantity Q distributed over the area will be assumed to be equal to

$$Q = \int b dS \tag{34}$$

with a luminous flux filling the surrounding space and producing an illumination E on a surface in that space equal to the flux per unit of area, or

$$E = \frac{F}{S}. \tag{35}$$

Unit Disk.[2]—Concerning a body charged with electricity, there are two points to bear in mind: (1) the electricity of density σ and total quantity $Q = \int \sigma dS$ on the surface of the charged body, and (2) the flux of force throughout the surrounding space, there being $4\pi Q$ lines of force for a quantity Q of electricity. At present the fluid theory of electricity does not have the same meaning that it did in Franklin's time, but nevertheless the idea of a surface density of electricity is very useful. Similarly, there may be two distinct ideas concerning light: (1) a surface distribution of light over a luminous area of *brightness* or *specific quantity* b, and total quantity $Q = \int b dS$, and (2) a luminous flux filling

[1] This chaper consists essentially of the paper, with slight modifications by the author, of Dr. E. B. Rosa, *Bull. Bur. Stand.*, vol. 6, p. 543, in which he acknowledges the writings of Blondel, Palaz, Liebenthal, Hering, Kennelly, Sharp, Hyde, and Jones.

[2] By unit disk and unit sphere is meant a disk or sphere whose linear dimensions are negligible compared with the distance from source to receiver.

the surrounding space and producing an illumination E on any body equal to the flux per unit of area,

$$\text{or } E = \frac{F}{S}.$$

So far, illumination and intensity have been defined in terms of the flux. Their values in terms of the *quantity of light on the surface of the luminous source* will now be determined.

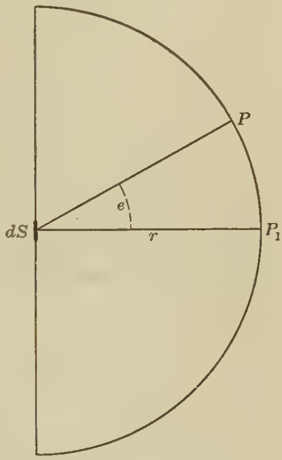


FIG. 82.—A small surface source.

The *illumination from a very small source* is inversely proportional to the square of the distance from the source and directly proportional to the brightness of the source. Hence for a luminous plane of area dS (Fig. 82) it is possible to write

$$E_{P_1} = \frac{Q}{r^2} = \frac{bdS}{r^2}, \tag{36}$$

where Q is the total quantity of light on the disk, and the radiation to P_1 at a distance r is normal. For a point P at an angle e from the normal the illumination would be

$$E_P = \frac{bdS \cos e}{r^2} = \frac{Q \cos e}{r^2}. \tag{37}$$

The *total flux over the hemisphere illuminated by the disk* is

$$F = \int_0^{\frac{\pi}{2}} E_P 2\pi r^2 \sin e de = Q \int \frac{2\pi r^2 \sin e \cos e \, de}{r^2}$$

$$= \Big[\pi Q \sin^2 e\Big]_0^{\frac{\pi}{2}} = \pi Q. \tag{38}$$

Thus the total luminous flux F from a small plane disk is π times the quantity of light Q on the disk.[1]

The *average illumination over the hemisphere* of radius r is

$$\frac{F}{2\pi r^2} = \frac{Q}{2r^2}, \tag{39}$$

[1] In electrostatics the total flux is 4π times the quantity Q. The difference is due, first, to the fact that the luminous disk is supposed luminous on one side only and hence there is radiation only on one side, whereas the electric flux would be on both sides; secondly, the cosine law makes the average flux only half what it would be if the factor $\cos e$ were omitted.

whereas the maximum illumination E_n normal to the disk is $\frac{Q}{r^2}$. Thus the mean is half the maximum. The intensity I has been defined as the *angular rate of flux* in any particular direction. It is, therefore, proportional to the illumination produced in the given direction. Thus, for the luminous disk,

$$I_n = \text{maximum intensity (normal)} = Q. \tag{40}$$

$$I_{hs} = \text{mean hemispherical intensity} = \frac{Q}{2}. \tag{41}$$

$$I_s = \text{mean spherical intensity} = \frac{Q}{4}. \tag{42}$$

Thus

$$F = \pi I_n = 4\pi I_s. \tag{43}$$

That is, the intensity is numerically equal to the total quantity of light on the small disk *for all points on the normal.* It *decreases to zero* in passing 90 deg. away from the normal, having a mean value of half the maximum for the whole hemisphere, and is on the average only one-fourth the maximum for the whole sphere. It may, therefore, be said that the *hemispherical reduction factor* for the disk is one-half, and the mean *spherical reduction factor* is one-fourth, the disk being supposed luminous on one side only.

Since the total flux F from an area is πQ, where Q is the quantity of light on the area, the flux from a unit of area is πb. This is the radiation E'. Hence, in general

$$E' = \pi b. \tag{44}$$

For a small sphere of radius a the total flux is

$$\begin{aligned} F &= E' \times \text{ surface} \\ &= \pi b \times 4\pi a^2 = \pi Q. \end{aligned} \tag{45}$$

$$\text{Also, } F = 4\pi I$$

$$\therefore\ I = \frac{Q}{4}. \tag{46}$$

That is, for a unit sphere the intensity is one-fourth the quantity of light on the sphere. If the distribution of light over the sphere is not uniform, the *mean spherical intensity* is still one-fourth the total quantity of light on the sphere, as it is also for a disk. In other words, a sphere produces the same illumination at a given point as a disk of the same diameter and same brightness placed so that the radiation from the disk to the point is normal.

Extended Source.—If dS be an element of a plane radiating surface of brightness b, defined by the equation

$$Q = bS, \tag{47}$$

that is, the quantity of light Q is equal to the product of b into the surface S—b is the value of the quantity Q when the surface is unity, and is the quantity of light per unit of area measured in candles—then the intensity I of such a source (or of any source) would be measured by comparing it experimentally with a standard light source, and it is equal to the intensity of a point source or unit sphere which produces the same illumination on a given test screen (of a photometer). Thus, while the intensity of a light source is *defined* as the luminous flux per unit solid angle, it is *determined* by comparison with a concrete standard by means of the illumination produced on a test screen at a

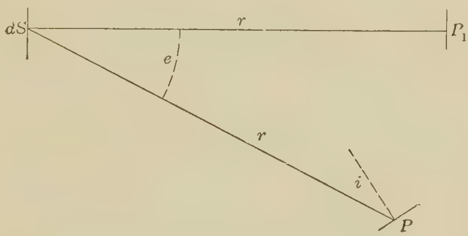


FIG. 83.—A small circular source.

convenient distance, using a photometer and employing the law of inverse squares.

In Fig. 83 the illumination at P_1 in the normal to dS is

$$E_1 = \frac{bdS}{r^2}, \tag{48}$$

while the illumination at P, the angles of emergence and incidence being e and i respectively, is

$$E_2 = \frac{bdS \cos e \cos i}{r^2}. \tag{49}$$

The cosine law is assumed to hold exactly for both surfaces.

To calculate the illumination due to a large circular disk of brightness b and any radius a on a small plane area P_1, normal to the axis of the disk and situated on the axis at distance r from

the disk (see Fig. 84), the effect of each elementary circular ring of the disk is integrated. Thus, in Eq. (49), putting $dS = 2\pi x dx$,

$$E = b\int_o^a \frac{2\pi x dx \cos e \cos i}{r^2 + x^2} \tag{50}$$

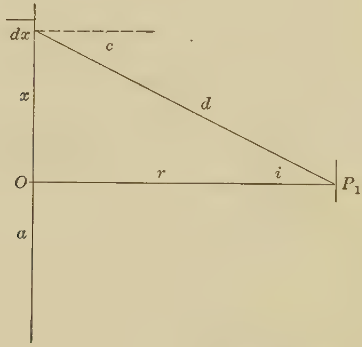


FIG. 84.—A large circular source.

$$\text{Since } \cos e = \cos i = \frac{r}{\sqrt{r^2 + x^2}} \tag{51}$$

$$E = \pi b \int^a \frac{2xdxr^2}{(r^2 + x^2)^2}$$

$$= \pi b \left[\frac{-r^2}{r^2 + x^2} \right]_o^a = \pi b \left[1 - \frac{r^2}{r^2 + a^2} \right] \tag{52}$$

$$\text{or } E = \frac{\pi b a^2}{r^2 + a^2} = \frac{bS}{r^2 + a^2} = \frac{Q}{r^2 + a^2}, \tag{53}$$

where Q is the product of the surface of the disk into the brightness b, and is the total quantity of light upon the disk measured in candles. If the disk were very small, Q would be the same as the maximum intensity I_n of the source; but for an extended source a distinction must be made between the equivalent *intensity* I_o and the surface integral of the *brightness* b, which is Q. The latter has been called the quantity of light upon the disk; it is proportional to the total luminous flux F coming from the extended source, and is equal to F/π(Eq. (38)). Q and F really measure the same thing, except that Q is located on the source and is measured in candles, while F is located in the surrounding

space and is measured in lumens; their ratio is constant as $F = \pi Q$ always.[1]

For the disk above mentioned, the illumination E on a small plane normal to the axis is proportional to the total quantity of light Q on the extended source (the circular disk) and inversely proportional to the square of the distance d from P_1 to the *edge of disk.* This holds true for all distances r from zero to infinity. Thus the *law of inverse squares holds generally* for the illumination along its axis due to a circular disk of any size, but the distance is measured not to the center of the disk, but to the edge.

Thus,

$$E = \frac{I}{r^2} \text{ for a point source or a unit disk,} \tag{54}$$

and

$$E = \frac{Q}{d^2} \text{ for an extended disk.} \tag{55}$$

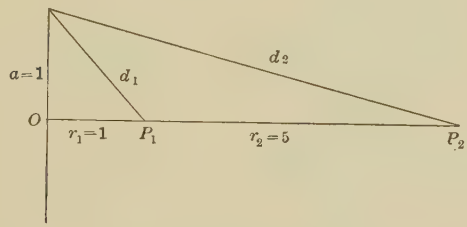


FIG. 85.—A large circular source.

To illustrate the rate of variation of the illumination with the distance, let $a = I$, $r_1 = 1$, $r_2 = 5$ (Fig. 85).

[1] The total quantity of electricity on a disk of area S is equal to the integral of the surface density σ over the area.

$$Q = \int \sigma dS$$
$$= \sigma S \text{ when } \sigma \text{ is uniform.}$$

The brightness b of a source corresponds to the surface density of electricity σ, and the total quantity of light over a surface is, in the same way, the surface integral of b. Thus

$$Q = \int b dS$$
$$= bS \text{ when } b \text{ is uniform over the area } S.$$

For a sphere, the surface $S = 4\pi a^2$. Therefore, for a spherical source $Q = 4\pi a^2 b$, whereas the intensity $I = \pi a^2 b$. That is, the intensity I of a spherical source is one-fourth of Q, and is equal to the light on a disk of radius a and brightness b. That is, the intensity of the sphere is equivalent to that of a disk of the same diameter and the same brightness for points at a great distance.

In the first case for the point P_1, $E_1 = \frac{Q}{d_1^2} = \frac{\pi b}{2}$.

In the second case for the point P_2, $E_2 = \frac{Q}{d_2^2} = \frac{\pi b}{26}$.

Thus in the first case the distance is five times less and the illumination is thirteen times more, instead of twenty-five times more as it would be if the light Q were all concentrated at the center of the disk. If $r = o$, the illumination is πb, or twice as much as at P_1, and not infinite as it would be at zero distance from a point source.

This theorem is useful in measuring the radiation from walls, as the radiating area may be quite large and the photometer relatively near.

Infinite Plane.—The *radiation from an infinite plane* S (Fig. 86) upon a unit area of a parallel plane T is found by integrating Eq. (52) to infinity. Thus

$$E = \pi b \int_o^\infty \frac{2xdx \cdot r^2}{(r^2 + x^2)^2} = \pi b \left[\frac{-r^2}{r^2 + x^2}\right]_o^\infty = \pi b. \qquad (56)$$

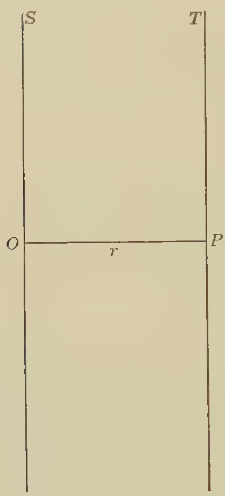


Fig. 86.—Radiation from an infinite on a unit area.

Fig. 87.—Radiation from an infinite plane on an infinite area.

Thus the flux density or *illumination* at any point P on the T plane is π times the brightness b on the radiating plane S and is independent of the distance r.

From each unit of area of S having a brightness b the total flux is πb, as shown above. The resultant flux at all points is

the same as though the total flux πb from each unit of area of S was confined to a cylindrical tube of unit area perpendicular to S, in which case the flux density would, of course, be constant at all sections—that is, at all distances (see Fig. 87).

A Large Spherical Source.—If a surface S_1 (supposed a portion of a spherical surface of radius r_1) has a brightness b and subtends a small solid angle ω, the illumination which it produces at P (Fig. 88) is

$$E = \frac{bS_1}{r_1^2} = \frac{b\omega r_1^2}{r_1^2} = b\omega. \tag{57}$$

A second surface S_2 of the same brightness will produce the same illumination at P provided it subtends the same angle ω. A

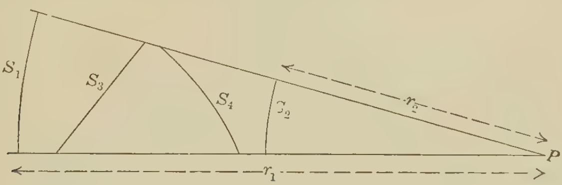


FIG. 88.—Section of large spherical source.

third surface S_3 at any angle will also produce the same illumination at P if it has the same brightness b and subtends the same solid angle ω.

For the radiation of each element, dS_3 is

$$\frac{bdS_3}{r_3^2}\cos e = \frac{b\omega r_3^2}{r_3^2} = b\omega \tag{58}$$

as before. So also with the curved surface S_4. In every case the greater distance from P or the inclination of the angular position is compensated by the greater area included within the given (small) solid angle.

Now calculate the illumination at P due to a large luminous sphere of radius a and brightness b, r being the distance from P (Fig. 89) to the center of the sphere. Let the solid angle APB subtended at P by the sphere be subdivided into a large number of elementary solid angles. Each of the latter encloses an area, as S_1, on the surface of the sphere, and also a corresponding area S_1', on the circular disk AB. As has just been seen, the illumination produced at P by each spherical area S_1, S_2, etc. is exactly the same as that produced by the corresponding plane areas S_1', S_2', etc. of the disk, if the brightness b is the same for the disk as for the sphere. Therefore the illumination at P due to the

entire sphere is the same as that due to the disk AB, and the latter may be calculated by Eq. (55). That is,

$$E = \frac{Q}{d^2},$$

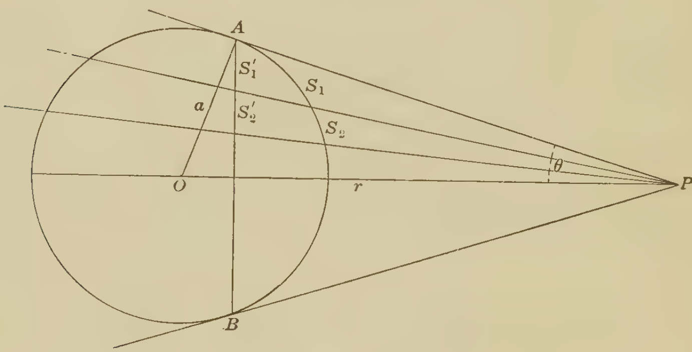


FIG. 89.—A large spherical source.

where Q is the quantity of light on the disk and d is the distance AP from the point P to the edge of the disk. Q is equal to b times the area of the disk, or

$$Q = \pi(a \cos \theta)^2 b \tag{59}$$

$$d = r \cos \theta \tag{60}$$

$$\therefore E = \frac{Q}{d^2} = \frac{\pi a^2 b}{r^2}$$

$$= \frac{1}{4}\frac{Q_s}{r^2} = \frac{I_s}{r^2}, \tag{61}$$

where Q_s is the quantity of light on the sphere $= 4\pi a^2 b$ and is constant for all distances, and I_s is the intensity of the equivalent point source. Therefore the illumination produced by a *sphere of any size* is inversely proportional to the square of the distance measured *from its center*, and is equal to the intensity of a point source (or unit sphere) having the same total amount of light divided by the square of the distance. In other words, the inverse-square law holds just as rigorously for large spheres as for points (always, of course, assuming the cosine law to hold for the spherical surfaces, and the brightness b to be uniform over the sphere). When P comes very near to the surface the area

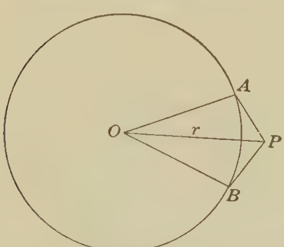


FIG. 90.—A large spherical source (P near).

AB of the sphere (Fig. 90) available for illuminating P is very small, but the distance is just enough less to counterbalance. When P comes up to the surface, $r = a$, and

$$E = \pi b \tag{56}$$

the same as for an infinite plane, to which the sphere is equivalent when the distance from the surface is reduced to zero.

The same result is reached more simply as follows:

A luminous sphere of radius a and uniform brightness b gives off a total flux $F = 4\pi a^2 \times \pi b = 4\pi^2 a^2 b$. This produces an illumination on the inner surface of any concentric sphere, which by symmetry will be everywhere the same, and $F = 4\pi r^2 E$.

$$\therefore E = \frac{\pi a^2 b}{r^2} = \frac{I}{r^2}. \tag{62}$$

Therefore the *illumination produced by a sphere* of uniform brightness is inversely proportional to the square of the distance from the center for all distances from the surface of the sphere to infinity.

A Hollow Spherical Source.—From what precedes it is seen that the illumination at any point P due to the hollow hemisphere ACB (Fig. 91) is the same as that due to the circular disk AOB. The latter is

$$E = \frac{\pi a^2 b}{AP^2}. \tag{63}$$

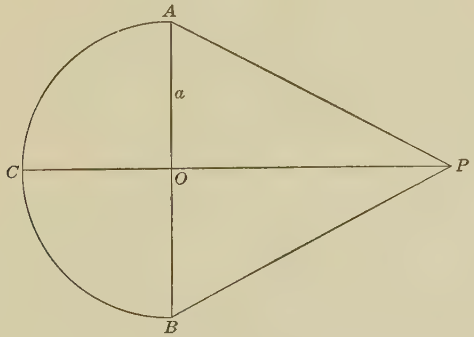


FIG. 91.—A hollow spherical source.

When OP is reduced to zero, the illumination due to the disk is πb, and hence the illumination at O on an elementary plane area in the diametral plane is π times the brightness b of the surface of the sphere. It has already been seen that the total flux from a unit of surface of brightness b is πb. Hence the total flux

through unit area S at O, due to the hemisphere, is equal to the total flux through the hemisphere due to the luminous unit area S, the brightness b being the same in each case.

This is a particular case of a more general proposition, namely, *the flux due to any surface S passing through an element dS is equal to the flux due to the latter passing through the former,* the brightness being the same in each case.

As shown above, the illumination E at P_1, due to S_1 (Fig. 92), is equal to $b\omega$, where b is the brightness of S_1 and ω is the (small) solid angle subtended at P_1 by S_1; this is independent of the

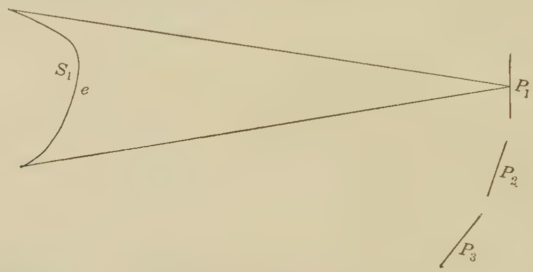


FIG. 92.—Illumination independent of shape of source.

shape of S_1 or its distance from P_1. The flux F passing through dS at P_1 is, therefore,

$$F = bd\omega dS \cos\theta, \text{ over the area of } S_1 \tag{64}$$

or

$$F = bdS\int \cos\ \theta\ dw. \tag{65}$$

Similarly, the flux due to dS at P_1 passing through S_1 is

$$\begin{aligned} F &= \int bdS\ \cos\ \theta\ d\omega \\ &= bdS\int \cos\theta\ d\omega. \end{aligned} \tag{66}$$

In the integration every element dw of the solid angle is to be multiplied by the cosine of the angle it makes with the normal to the area dS.

As the same theorem holds for the elementary areas P_2 and P_3, etc., it holds for their sum, and hence for a finite surface S_2 (Fig. 93). Hence, generally, *the luminous flux due to a surface S_1 passing through S_2 is equal to the luminous flux due to S_2 passing through S_1,* the brightness being the same in each case. This is analogous to the theorem that the magnetic flux due to a magnetic shell S_1, which passes through a second shell S_2, is equal to that part of the magnetic flux S_2 which passes through S_1, the strength

of the shells being supposed the same. Or, again, the number of lines of force due to unit current in an electric circuit S_1 passing through S_2 is equal to the number of lines of force due to unit current in S_2 passing through S_1. It follows from the above that in any closed surface of uniform brightness the flux passing out from any portion S_1 is equal to that received from the remainder of the surface S_2.

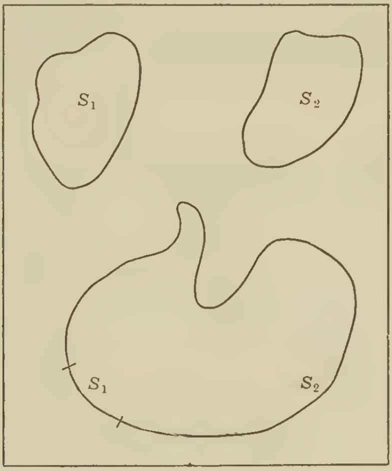


FIG. 93.—Surface source.

A Hollow Sphere.[1]—Suppose a hollow sphere (Fig. 94) of uniform surface having a coefficient of diffuse reflection m.

$$1 - m = \text{absorption.}$$

Let E = illumination at S.

$$E' = mE = \text{radiation from } S.$$

$$b = \frac{mE}{\pi} = \text{brightness of } S.$$

The flux falling on S_1 due to S is

$$S_1 dE_1 = \frac{eSS_1 \cos^2 \varphi}{r^2} = \frac{mE}{\pi} \cdot \frac{SS_1 \cos^2 \varphi}{r^2}. \tag{67}$$

But $r = 2a \cos \varphi$

$$r^2 = 4a^2 \cos^2 \varphi$$

$$\frac{\cos^2 \varphi}{r^2} = \frac{1}{4a^2}$$

$$\therefore dE_1 = \frac{mE}{\pi} \cdot \frac{S}{4a^2} \tag{68}$$

[1] See LIEBENTHAL, "Praktische Photometrie," p. 301.

and this is the same for every element of the sphere. Hence *every element* illuminates all other elements equally. Therefore the *indirect* illumination of the sphere must be the same everywhere, no matter how unequal the direct illumination may be. That is, a light at L illuminates the sphere unequally, directly. But that part of the total illumination due to diffuse reflection is, notwithstanding, everywhere equal.

A light of mean spherical intensity I sends out $4\pi I$ lumens.

Of this there is reflected, first, $4\pi m I$ lumens.

Of this there is reflected, second, $4\pi m^2 I$ lumens.

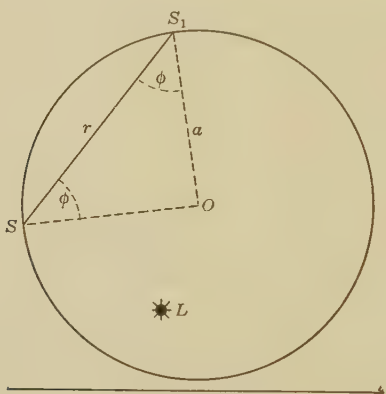


FIG. 94.—The hollow sphere.

Of this there is reflected, third, $4\pi m^3 I$ lumens, and so on. Therefore the total amount of flux reflected is

$$4\pi I m\left[1 + m + m^2 + m^3 + \ . \ . \ . \ . \ .\right] = 4\pi I \frac{m}{1 - m} = F_2. \quad (69)$$

Hence the secondary illumination everywhere equal on the surface of the sphere is

$$E_2 = \frac{F_2}{4\pi a^2} = \frac{mI}{(1 - m)a^2}. \quad (70)$$

Thus the indirect illumination is proportional to I, and the lamp of intensity I may be anywhere in the sphere. It is equal to $\frac{m}{1 - m}$ of what the direct illumination would be if the source were placed at the center of the sphere. For example, let a 16-

c.-p. lamp be placed within a sphere having a radius of 1 m. and a coefficient of diffuse reflection of 0.8.

Then $I = 16$

$$a = 1 \text{ m.}$$
$$m = 0.8$$
$$E_2 = \frac{0.8}{0.2} \times \frac{16}{1} = 64 \text{ meter-candles}$$
$$E_1 = \frac{I}{a^2} = 16 \text{ meter-candles, if lamp is in the center}$$
$$E = E_1 + E_2 = 80.$$

Thus the total illumination is five times what it would be if the walls were perfectly black. This may be put in another way; of the total illumination of 80 meter-candles, 20 per cent is absorbed by the walls. Therefore the lamp or source must supply only one-fifth of the total, just enough to make good the constant loss.

Thus the source is analogous to an exciter of electric waves that must supply just enough energy to make good the resistance losses in the circuit.

Luminous Flux within an Enclosure.—If the inner surface of the hollow sphere has a brightness b and a specific radiation $E' = \pi b$, a unit disk at the center of the sphere will receive an illumination $E = \pi b$. The same will be true wherever the unit disk is placed within the sphere and whatever the orientation of the disk; that is, the flux falling on the disk will be everywhere the same. The flux density within the hollow sphere is therefore everywhere uniform and equal to πb. The flux from a point source is thought of as in straight lines, and a disk can be placed normal to the direction of the flux. But within the sphere the flux has a uniform value, but no resultant direction.

Within a cube or enclosure of any shape, of which the walls have a uniform brightness b or uniform specific radiation E', the same condition obtains as in the sphere—namely, the luminous flux is everywhere the same, and a small area will have the same illumination no matter where it is placed or how it is oriented. This is seen by dividing the space about any point P (Fig. 95) into elementary solid angles. The illuminations due to the surface subtending an angle ω is independent of the distance from P, and hence it will be πb for the total angle 2π on either side of the surface at P, no matter where the surface is placed.

The same is true, therefore, for the space between two infinite planes of brightness b. The illumination is πb on a small plane at P_1, P_2, or P_3 (Fig. 96), anywhere between the two radiating planes S and T no matter how they may be placed. Evidently,

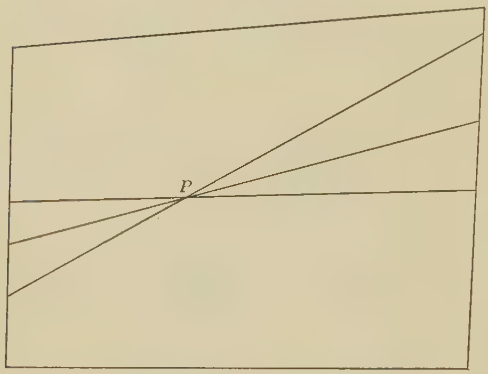


FIG. 95.—Illumination within an enclosure.

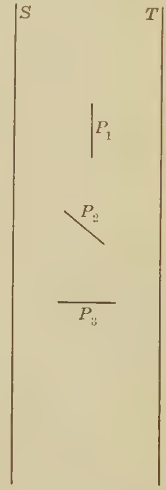


FIG. 96.—Illumination between infinite planes.

it is impossible to think of the flux as normal to the planes, as with the lines of force due to electrostatic charges on the planes S and T. The luminous flux normal to P_3 is the same as normal to P_1. On the other hand, the electric force normal to P_3 would be zero.

CHAPTER IX

ILLUMINATION CALCULATIONS AND DATA[1]

There are two basic methods of predetermining the illumination produced by a given lighting installation.

The first is known as the "point-by-point" method. It involves the distribution curves and candle-power values of a lamp with its reflector equipment, and the distance from the source to the point where the illumination is to be determined While this method is especially useful for determining the illumination upon specified points, it necessitates many tedious operations and does not take into consideration the light reflected from the ceiling and the walls.

The second method, known as the "flux-of-light" method, offers a more convenient and reliable means of solving an illumination problem. It is based on the assumption that the relation of the amount of light flux producing illumination on the working plane to the total light flux radiated by the lamp has a certain value when used under similar conditions with respect to type of reflector, size of room, height of unit, reflection from ceiling and walls, etc.

The Point-by-point Method.—This method will be found useful in determining the uniformity of distribution of illumination from a luminous source, for comparing with other sources, or for approximately determining the location of lamps for a desired distribution of illumination.

These calculations involve trigonometric equations, but sets of constants may be derived and tabulated so that results may be calculated by simple arithmetic. Assume the source of light to be located at a point S (Fig. 97) and let

I_a = candle power a deg. from the vertical.
E_n = illumination on a normal surface.
E_h = illumination on a horizontal surface.
E_v = illumination on a vertical surface.

[1] Much of the data in this chapter was obtained from the *Transactions of the Illuminating Engineering Society* and *Bulletins* from the Edison Lamp Works.

d = horizontal distance from vertical through lamp to point whose illumination it is desired to ascertain.
h = distance to lamp from horizontal plane.
l = distance direct from source to point considered.
a = the angle which the light rays make with the vertical.

Then the *illumination intensity at a point on a normal plane AB* will be

$$E_n = \frac{I_a}{l^2} = \frac{I_a}{h^2 + d^2} = I_a \frac{\cos^2 a}{h^2} \text{ foot-candles,} \tag{71}$$

$$\text{since } l = \frac{h}{\cos a} \text{ or } l^2 = \frac{h^2}{\cos^2 a}. \tag{72}$$

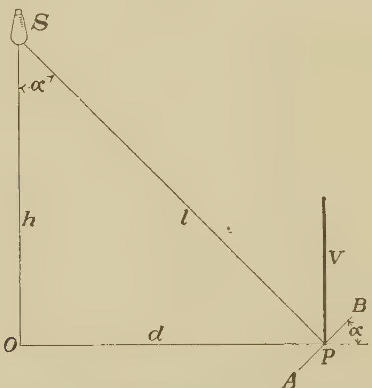


FIG. 97.—Diagrammatic representation of the relation of normal and horizontal illumination.

The *intensity of light on a horizontal plane OP* making an angle a with this normal plane will be $E_h = \frac{I_a \cos a}{l^2}$, and by substituting as before

$$E_h = I_a \frac{\cos a}{l^2} = I_a \frac{\cos a}{h^2 + d^2} = I_a \frac{\cos^3 a}{h^2} \text{ foot-candles.} \tag{73}$$

The horizontal distance d from the vertical may be found from the relation

$$d = h \tan a. \tag{74}$$

By the same reasoning the intensity of *illumination on a vertical plane PV* will be

$$E_v = I_a \frac{\sin a}{l^2} = I_a \frac{\sin a}{h^2 + d^2} = I_a \frac{\sin^3 a}{d^2} \text{ foot-candles,} \tag{75}$$

$$\text{since } l = \frac{d}{\sin a}. \tag{76}$$

If it is desired to know the candle power which will furnish a certain illumination, the foregoing equations may be transposed, giving

$$I_a = E_n l^2 = E_n(h^2 + d^2) = E_n \frac{h^2}{\cos^2 a}, \tag{77}$$

the *candle power required to illuminate a surface normal* to the rays,

$$I_a = E_h \frac{l^2}{\cos a} = E_h \frac{h^2 + d^2}{\cos a} = E_h \frac{h^2}{\cos^3 a}, \tag{78}$$

the *candle power necessary to give a horizontal illumination* E_h, and

$$I_a = E_v \frac{l^2}{\sin a} = E_v \frac{(h^2 + d^2)}{\sin a} = E_v \frac{d^2}{\sin^3 a}, \tag{79}$$

the *candle power sufficient to illuminate a vertical surface d* ft. from the source with an illumination of E_v foot-candles.

In Table 21 are given the values of $\sin \alpha$, $\cos \alpha$, $\tan \alpha$, $\sin^2 \alpha$, $\cos^2 \alpha$, $\sin^3 \alpha$, and $\cos^3 \alpha$, from 0 to 90 deg. The cosine and tangent values are for those values of α which increase from top to bottom, while the sine values are for those values of α increasing from the bottom toward the top.

Illumination on horizontal areas and the candle power to produce that illumination are the most common calculations in the distribution of light. In street lighting and in interior lighting where the lamps are equipped with opaque reflectors which throw the light downward on floors or surfaces dark in color, these equations are applicable and will give very approximate results. A set of constants per unit candle power for various heights of suspension of the source above the plane of reference may be tabulated, making preliminary determinations of such an installation comparatively simple. It will be seen that in the equation $E_h = I_a \frac{\cos^3 a}{h^2}$ the values of $\frac{\cos^3 a}{h^2}$ can be determined for various values of a and h, and designated by K; then $E_h = KI_a$ and $I_a = \frac{E_h}{K}$.

In Table 22 the values of $\frac{\cos^3 a}{h^2} = K$ are tabulated for heights from 1 to 20 ft. and for 0 to 40 ft. to the side.

This table can be extended by multiples of 10, the values of d being multiplied by 10 and the values of K divided by 100, as may be noted from the relations of the values of d and K for heights of 1 and 10 ft.

TABLE 21

Cos a	Tan a	a	Cos² a	Cos³ a		Cos a	Tan a	a	Cos² a	Cos³ a	
1.00	.000	0	1.00	1.000	90	.694	1.04	46	.482	.335	44
.99985	.0175	1	.999	.999	89	.682	1.07	47	.465	.317	43
.9994	.0349	2	.998	.998	88	.669	1.11	48	.447	.299	42
.998	.0524	3	.997	.996	87	.656	1.15	49	.430	.282	41
.997	.0699	4	.995	.993	86	.643	1.19	50	.413	.265	40
.996	.0875	5	.992	.988	85	.629	1.23	51	.395	.249	39
.994	.105	6	.989	.983	84	.615	1.28	52	.379	.233	38
.992	.123	7	.985	.978	83	.602	1.33	53	.362	.218	37
.990	.1405	8	.981	.971	82	.588	1.38	54	.345	.203	36
.988	.1584	9	.975	.963	81	.573	1.43	55	.329	.189	35
.985	.176	10	.970	.955	80	.559	1.48	56	.312	.175	34
.982	.194	11	.963	.946	79	.544	1.54	57	.296	.161	33
.978	.212	12	.957	.936	78	.530	1.60	58	.280	.149	32
.974	.230	13	.949	.925	77	.515	1.66	59	.265	.137	31
970	.249	14	.941	.913	76	.500	1.73	60	.250	.125	30
.966	.268	15	.933	.901	75	.485	1.80	61	.235	.113	29
.961	.287	16	.924	.888	74	.469	1.88	62	.220	.103	28
.956	.306	17	.914	.874	73	.454	1.96	63	.206	.0936	27
.951	.325	18	.904	.860	72	.438	2.05	64	.192	.0843	26
.945	.344	19	.894	.845	71	.423	2.14	65	.178	.0755	25
.939	.364	20	.883	.830	70	.407	2.25	66	.165	.0673	24
.933	.384	21	.872	.814	69	.391	2.35	67	.152	.0596	23
.927	.404	22	.859	.797	68	.375	2.47	68	.140	.0526	22
.920	.424	23	.847	.780	67	.358	2.60	69	.128	.0460	21
.913	.445	24	.834	.762	66	.342	2.75	70	.117	.0400	20
.906	.466	25	.821	.744	65	.325	2.90	71	.106	.0345	19
.899	.488	26	.808	.725	64	.309	3.08	72	.0955	.0295	18
.891	.509	27	.794	.707	63	.292	3.27	73	.0855	.0250	17
.882	.532	28	.779	.688	62	.275	3.48	74	.0759	.0209	16
874	.554	29	.764	.669	61	.259	3.73	75	.0670	.0173	15
.866	.577	30	.750	.649	60	.242	4.01	76	.0586	.0142	14
.857	.601	31	.735	.630	59	.225	4.33	77	.0506	.0114	13
.848	.625	32	.719	.610	58	.208	4.70	78	.0432	.00899	12
.838	.649	33	.703	.590	57	.191	5.14	79	.0363	.00686	11
.829	.675	34	.687	.570	56	.173	5.67	80	.0301	.00520	10
.819	.700	35	.671	.550	55	.156	6.31	81	.0244	.00379	9
.809	.726	36	.655	.529	54	.139	7.11	82	.0193	.00268	8
.798	.753	37	.637	.509	53	.122	8.14	83	.0148	.00181	7
.788	.781	38	.621	.489	52	.1045	9.51	84	.0109	.00115	6
.777	.810	39	.604	.469	51	.0872	11.43	85	.00760	.000661	5
.766	.839	40	.587	.449	50	.0697	14.3	86	.00486	.000339	4
.754	.869	41	.569	.430	49	.0523	19.08	87	.00274	.000144	3
.743	.900	42	.552	.410	48	.0349	28.64	88	.00122	.0000425	2
.731	.932	43	.534	.391	47	.0174	57.29	89	.000306	.0000053	1
.719	.966	44	.517	.372	46	.00	∞	90	.0000	.0000	0
.707	1.00	45	.500	.353	45						
Sin a			Sin² a	Sin³ a	a	Sin a			Sin² a	Sin³ a	a

TABLE 22

h	d	0′	2′	4′	6′	8′	10′	12′	14′	16′	18′	20′
1	α	00°	63° 25′	75° 55′	80° 30′	82° 50′	84° 20′	85° 15′	85° 55′	68° 25′	....	....
	K	1.00	.893	.0144	.00441	.00190	.000961	.000567	.000361	.000244	....	....
2	α	00°	45° 0′	63° 25′	71° 35′	76° 0′	78° 40′	80° 35′	81° 50′	82° 55′	83° 40′	84° 20′
	K	.250	.0883	.0224	.0079	.00355	.00191	.00111	.000722	.000473	.000336	.000246
3	α	00°	33° 40′	53° 5′	63° 25′	69° 25′	73° 20′	75° 55′	77° 55′	79° 25′	80° 30′	81° 30′
	K	.111	.0640	.0241	.00992	.00480	.00262	.00159	.00102	.000693	.000493	.000362
4	α	00°	26° 35′	45° 0′	56° 20′	63° 25′	68° 10′	71° 35′	74° 5′	76° 0′	77° 30′	78° 45′
	K	.0325	.0447	.0221	.0106	.00560	.00322	.00197	.00130	.000887	.00064	.00047
5	α	00°	21° 50′	38° 40′	50° 10′	58° 00′	63° 25′	67° 20′	70° 20′	72° 40′	74° 40′	76° 0′
	K	.0400	.0320	.0191	.0105	.00596	.00357	.00228	.00152	.00106	.00077	.00057
6	α	00°	18° 25′	33° 40′	45° 0′	53° 5′	59° 0′	63° 25′	66° 50′	69° 25′	71° 35′	73° 25′
	K	.0278	.0236	.0160	.00982	.00602	.00380	.00248	.00169	.00121	.00088	.00066
7	α	00°	15° 55′	29° 45′	40° 35′	48° 50′	55° 0′	59° 45′	63° 25′	66° 20′	68° 45′	70° 40′
	K	.0204	.0182	.0134	.00892	.00583	.00385	.00261	.00182	.00131	.00097	.00074
8	α	00°	14° 0′	26° 35′	36° 50′	45° 0′	51° 20′	56° 20′	60° 15′	63° 25′	66° 0′	68° 10′
	K	.0156	.0143	.0112	.00801	.00552	.00382	.00266	.00191	.00140	.00105	.00080
9	α	00°	12° 30′	24° 0′	33° 40′	41° 40′	48° 0′	53° 5′	57° 15′	60° 40′	63° 25′	65° 45′
	K	.0123	.0115	.00941	.00711	.00515	.00369	.00268	.00195	.00146	.00110	.00085
10	α	00°	11° 20′	21° 50′	31° 0′	38° 40′	45° 0′	50° 10′	54° 30′	58° 0′	61° 0′	63° 25′
	K	.0100	.00942	.00800	.00630	.00476	.00353	.00262	.00196	.00149	.00115	.00089

TABLE 22.—*Continued*

h	d	0′	4′	8′	12′	16′	20′	24′	28′	32′	36′	40′
11	α	00°	20° 0′	36° 0′	47° 30′	55° 30′	61° 10′	65° 25′	68° 35′	71° 0′	73° 0′	74° 40′
	K	.00826	.00685	.00441	.00254	.00150	.000925	.000597	.000407	.000284	.000207	.000154
12	α	00°	18° 25′	33° 40′	45° 0′	53° 5′	59° 0′	63° 25′	66° 50′	69° 25′	71° 35′	73° 20′
	K	.00694	.00592	.00400	.00245	.00151	.000950	.000620	.000425	.000300	.000219	.000165
13	α	00°	17° 5′	31° 35′	42° 40′	50° 55′	56° 55′	61° 35′	65° 5′	67° 55′	70° 10′	72° 0′
	K	.00592	.00517	.00366	.00235	.00148	.000965	.000640	.000440	.000316	.000232	.000174
14	α	00°	16° 0′	29° 45′	40° 40′	48° 50′	55° 0′	59° 45′	63° 25′	66° 20′	68° 45′	70° 40′
	K	.00510	.00453	.00333	.00222	.00145	.000965	.000653	.000455	.000329	.000243	.000184
15	α	00°	14° 55′	28° 5′	38° 40′	46° 50′	53° 5′	58° 0′	61° 50′	64° 55′	67° 20′	69° 25′
	K	.00444	.00401	.00305	.00212	.00142	.000964	.000661	.000469	.000340	.000253	.000192
16	α	00°	14° 0′	26° 35′	36° 50′	45° 0′	51° 20′	56° 20′	60° 15′	63° 25′	66° 0′	68° 10′
	K	.00391	.00357	.00279	.00200	.00138	.000954	.000668	.000476	.000349	.000262	.000200
17	α	00°	13° 15′	25° 10′	35° 15′	43° 15′	49° 40′	54° 40′	58° 45′	62° 0′	64° 40′	67° 0′
	K	.00346	.00319	.00256	.00189	.00134	.000937	.000668	.000485	.000358	.000269	.000207
18	α	00°	12° 30′	24° 0′	33° 40′	41° 40′	48° 0′	53° 10′	57° 15′	60° 40′	63° 25′	65° 45′
	K	.00309	.00287	.00235	.00178	.00129	.000927	.000667	.000488	.000364	.000276	.000213
19	α	00	11° 55′	22° 50′	32° 20′	40° 5′	46° 25′	51° 40′	55° 50′	59° 20′	62° 10′	64° 30′
	K	.00277	.00260	.00217	.00167	.00124	.000906	.000662	.000490	.000368	.000282	.000219
20	α	00°	11° 20′	21° 50′	31° 0′	38° 40′	45° 0′	50° 10′	54° 30′	58° 0′	61° 0′	63° 25′
	K	.0025	.00235	.00200	.00157	.00119	.000883	.000655	.000490	.000373	.000287	.000224

To make clear the manipulation of this table, the illumination on a horizontal surface 10 ft. below a luminous source and at a point 8 ft. to the side will be found. From the table it will be seen that for a height of 10 ft., and 8 ft. from the vertical, $K = 0.00476$ and $a = 38$ deg. 40 min. If the candle power of the source at 38 deg. 40 min. from the vertical is 200 candle power, then the horizontal illumination at a point 8 ft. from a vertical through the lamp will be

$$200 \times 0.00476 = 0.952 \text{ foot-candle.}$$

The candle power of the source in that direction necessary to give an illumination of 0.952 foot-candle at that point will be

$$\frac{0.952}{0.00476} = 200 \text{ c.p.}$$

Theoretical Curves for Uniform Illumination.[1]—It is often desirable to know the distribution of light from a luminous source which will give an approximately uniform illumination.

In order to obtain uniform illumination from one lamp, recourse is made to the expression $E_h = \frac{I_a}{h^2} \cos^3 a$, which is transposed into the form $I_a = \frac{E_h h^2}{\cos^3 a}$, where E_h is the horizontal illumination in foot-candles, a the angle which the luminous rays make with a vertical through the source, I_a the candle power of the source of light a deg. from the vertical, and h the height of the lamp above the working plane.

For uniform illumination E_h and h^2 will be constant and I_a at various values of a must vary inversely as $\cos^3 a$. A polar curve showing this relation is given in Fig. 98, which represents the distribution of candle-power intensity of a lamp in a vertical plane which will uniformly illuminate the area beneath it. Obviously, the area thus illuminated by one lamp is limited. In order, therefore, to illuminate larger areas uniformly, a number of lamps must be so arranged that the distribution of light will produce the desired effect. Obviously, a number of lamps having a distribution of light similar to that shown in Fig. 98 would not suffice, since each lamp would uniformly illuminate a circular area as indicated in Fig. 99, and the areas between the circles shown shaded in the figure would receive no light.

[1] Wohlauer, A. A., *Elec. World*, vol. 50, p. 1207.

It follows, then, that the polar candle-power distribution must be modified and the lamps so placed that the illumination from lamps near together will overlap. Such a condition is repre-

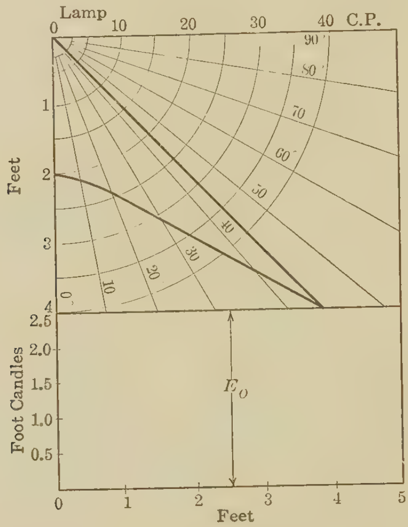


Fig. 98.—Distribution curve for uniform illumination by means of one source.

sented by Fig. 100, in which the small circles represent the location of the lamps and the large circles concentric with them represent the areas illuminated by the respective lamps.

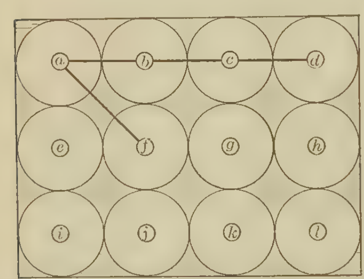


Fig. 99.—Sporadical uniform illumination.

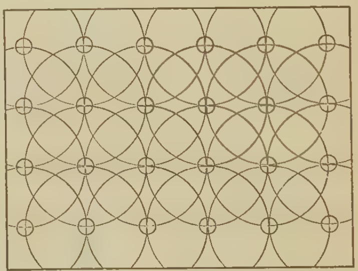
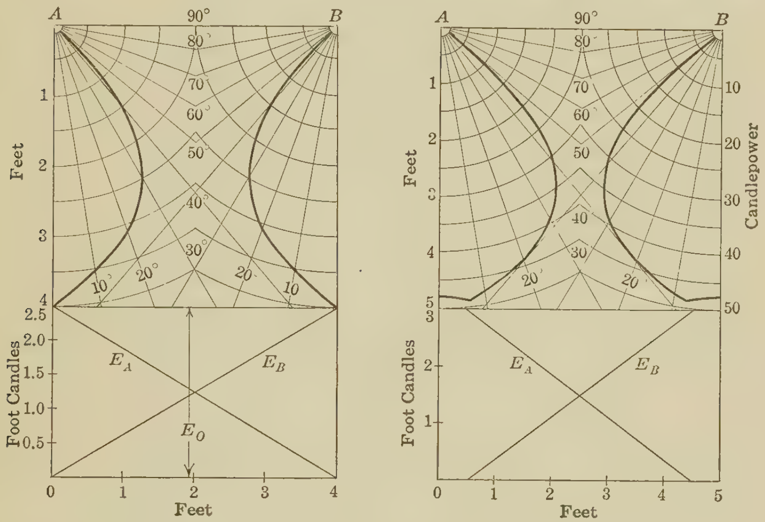


Fig. 100.—Uniform illumination by overlapping straight illumination curves.

It will be readily understood that, in order to secure approximately uniform illumination with a number of lamps, the illumination due to each lamp must decrease with departure from a position beneath the source. Polar candle-power curves of

different shapes, whereby these conditions may be realized, are shown in the following illustrations. To simplify matters, consideration will be given only to the area beneath and between two lamps A and B, and a study will be made of the distribution of light in a vertical plane through the centers of the lamps which will uniformly illuminate this area. The simplest way of effecting this is indicated in Fig. 101. There the vertical candle power of each lamp is of sufficient value to give the desired intensity E_0 beneath the source, and of sufficient intensity in other direc-



FIGS. 101 and 102.—Polar curves for uniform illumination.

tions that the intensity of illumination decreases in a straight line to zero beneath the other lamp.

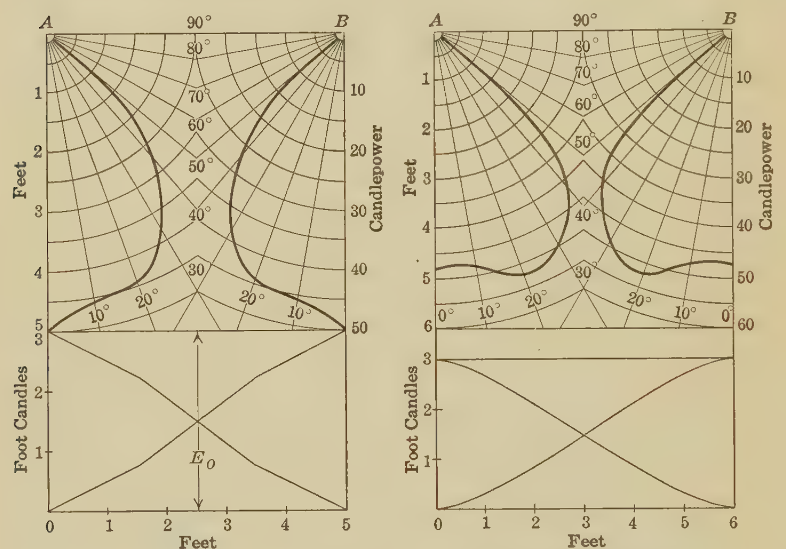
This is the simplest form of curve for uniform illumination with a number of lamps. It is evident, however, that with four lamps placed at the corners of a square the illumination along the sides of the square will be uniform, but not so at the intersection of the diagonals of the square. The illumination of this point is four times the intensity at a distance equal to $0.5\sqrt{2d^2}$ from a point beneath one lamp, or $1.17E_o$. In this figure it may be seen that the ratio

$$\frac{d}{h} = 1. \qquad (80)$$

It often happens that it is impractical to locate lamps according to this relation. If the ceilings happen to be low and the illu-

minants of high candle power, the lamps must be placed further apart.

Under these conditions the polar curve must be made up of a combination of those shown in Figs. 98 and 101, *i.e.*, each lamp must uniformly illuminate a section of the area beneath itself from which the illumination may then assume a constant decline, reaching zero value where the uniform illumination due to the next lamp begins. The curves of this nature are shown in Fig. 102. Another form of polar curve for uniform illumination is



FIGS. 103 and 104.—Polar curves for uniform illumination.

shown in Fig. 103. The equations of these curves are too complicated for practical purposes.

The general case of polar curves yielding uniform illumination is indicated by Fig. 104. The equation for curves of this nature is

$$I_a = E_o\left(\frac{d - h \tan a}{d} + c \sin \frac{4\pi h \tan a}{d}\right), \tag{81}$$

where c is a constant which must be determined for each particular case.

Flux-of-light Method.—While the point-by-point method of calculating illumination is fundamental, it will be found too cumbersome for general use. Neither does it take into account

the light reflected from walls and ceiling, or other factors which may be present under various conditions.

The flux-of-light method is based on the assumption that, under similar conditions as to type of luminaire, color of walls and ceiling, size of room, etc., the lumens on the working plane will be a definite percentage of the total emitted by the lighting unit or units.

The lumens on the working plane will equal the average foot-candle intensity (E_o) multiplied by the room area (S) in square feet. This value divided by the lumens per lamp (F_t) times the number of lamps (N) gives the percentage mentioned above and known as the "coefficient of utilization" given in Table 27.

Since lamps decrease in candle power during their life, as shown in Figs. 126 and 127, and the accumulations of dust and dirt further reduce the available light, the calculations must involve another factor known as the "depreciation factor." This factor may vary from 1.2 for an installation in a favorable location and carefully maintained to 1.7 for one in a dirty location and receiving no attention.

The flux-of-light method may be used to calculate the size of lamp, the number of lamps, or resulting illumination, as will be seen from the following.

If the number of lamps or outlets are decided upon and the intensity of illumination for the desired service determined, the lumens per lamp (or per outlet) can be found from the equation

$$F_t = \frac{E_o DS}{NC} \tag{82}$$

where F_t = the total lumens per lamp when new (Table 23).
E_o = the average illumination in foot-candles (Table 24).
S = the room area in square feet.
N = the number of lamps.
C = the coefficient of utilization (Tables 27 and 28).
D = the depreciation factor (1.2 to 1.7).

To find the illumination on the working plane for a given installation, transpose the above equation as follows:

$$E_o = F_t \frac{NC}{SD}. \tag{83}$$

To find the number of lamps of a certain size

$$N = \frac{E_o DS}{F_t C}. \tag{84}$$

TABLE 23

Mazda Standard Multiple Lamps

Watts	Approximate lumens (1922) 110, 115, 120 volts			Clear-glass lamps 220, 230, 240, 250 volts	
	Type B	Type C	"Daylight"	Type B	Type C
10	80				
15	130				
25	240[1]	......	.....	200	
40	400				
50	510[1]	500[2]	340	450	
60	620				
75	...	880[2]	600		
100	...	1,300	880	...	1,000
150	...	2,100	1,450	...	
200	...	3,100	2,100	...	2,500
300	...	4,900	3,400	...	4,300
500	...	9,000	6,150	...	7,850
750	...	14,000	.....	...	12,500
1,000	...	20,000	.....	...	17,800

[1] Also made in mill-type construction giving 200 and 435 lumens respectively.

[2] White Mazda in 50-watt size gives 440 lumens, and in 75-watt size gives 780 lumens.

TABLE 23.—*Continued*

Mazda Standard Series Street Lamps (Type C)

Amperes	Rated candle power	Lumens	Average volts	Lumens per watt
	60	600	8.1	13.5
	80	800	10.0	14.6
5.5	100	1,000	12.0	15.2
	250	2,500	27.1	16.8
	400	4,000	45.1	16.1
	60	600	6.8	13.4
	80	800	8.4	14.5
6.6	100	1,000	10.0	15.2
	250	2,500	23.1	16.4
	400	4,000	37.0	16.4
	600	6,000	54.7	16.6
	60	600	6.3	12.7
	80	800	7.8	13.6
7.5	100	1,000	9.4	14.2
	250	2,500	21.	15.9
	400	4,000	33.8	15.8
	600	6,000	50.3	15.9
15	400	4,000	14.8	18.0
	600	6,000	15.5	19.3
20	1,000	10,000	25.9	19.3
	1,500	15,000	38.5	19.5
	2,500	25,000	60.6	20.6

TABLE 24

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Aisles in factories, stairways, passageways	1– 2
Armories, public halls	3– 6
Art galleries (walls)	8– 20
Assembling of manufactured articles:	
Rough	3– 6
Medium	5– 10
Fine	8– 15
Extra fine	12– 50
Athletic fields	1– 3
Auditoriums (exclusive of stage)	2– 4
Automobiles:	
Garages	4– 8
Manufacturing (see Machine Shops, etc.)	5– 10
Showroom (see Show Windows)	8– 12
Storage	1– 2
Interiors of limousines; buses	0.02– 1
Painting	40– 50
Bakeries	5– 10
Ballrooms	3– 8
Banks:	
General	6– 10
Desk, cashier's window	8– 12
Barber shops	6– 10
Baths, public:	
Dressing rooms	2– 4
Swimming pool	3– 5
Billboards:	
Light	10– 30
Dark	20– 50
Billiard rooms:	
General	2– 4
Tables	8– 12
Boilers, engine rooms, and power houses:	
Boilers, coal and ash handling, storage-battery rooms	2– 4
Auxiliary equipment, oil switches and transformers	3– 6
Switchboards, engines, generators, blowers, and compressors	4– 8
Book binding:	
Folding, assembling, pasting, etc	3– 6
Cutting, punching, and stitching	5– 10
Embossing	8– 12

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Bowling alleys:	
Alley, runways, and seats	2– 4
Pins	8– 12
Candy making:	
Cooking furnaces, cooling slabs, cream beater machines, dipping (hand), molding, revolving pan, spinning bench, weights and measures, wrapping and packing	4– 10
Canning and Preserving:	
Cooking, assorting, cleaning, cutting, peeling, hand filling, machine filling	5– 10
Carpenter shops (see Woodworking)	
Cars:	
Baggage	3– 6
Day coaches, subways	4– 8
Dining	4– 8
Mail	5– 15
Pullman	4– 8
Street railway	3– 6
Chemical works:	
Hand furnaces, boiling tanks, stationary driers, stationary or gravity crystallizing	2– 4
Mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallization, bleaching	3– 6
Tanks for cooking, extractors, percolators, nitrators, electrolytic cells	4– 8
Laboratory	8– 12
Churches	3– 6
Clay products and cements:	
Grinding, filter presses, kiln rooms	2– 4
Molding, pressing, cleaning, and trimming	3– 6
Enameling	4– 8
Coloring and glazing	6– 12
Cloth products:	
Light goods	6– 12
Dark goods	10– 20
Coal breaking and washing, screening	2– 4
Construction, general:	
Indoor	2– 4
Outdoor (rough)	0.5– 2
Corridors	1– 2
Court rooms	4– 6
Courts:	
Handball, squash, tennis	7– 10

Table 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Dairy products:	
Separators, evaporators, churns, molds, presses, pasteurizing, bottling, canning, labeling, ice cream freezing	4– 8
Depots:	
Baggage rooms	3– 6
Train sheds, concourse	2– 5
Waiting rooms	3– 6
Drafting	10– 20
Drill grounds, outdoor	0.2– 2
Electric manufacturing:	
Storage battery, molding of grids	4– 9
Coil and armature winding, mica working, insulating, molding, wire insulating	6– 12
Lamp manufacturing (exclusive of mounting)	5– 20
Elevators:	
Freight and passenger	3– 6
Grain (see Milling)	
Engraving	10– 50
Erecting	2– 6
Factories (see Machine Shop, Foundries, etc.)	
Fire engine house:	
When alarm is turned in	4– 6
At other times	1– 2
Forge shops and welding:	
Rough forging and welding	4– 8
Fine welding	6– 12
Foundries:	
Charging floor, tumbling, cleaning, pouring, and shaking out	3– 6
Rough molding and core making	4– 8
Fine molding and core making	6– 12
Glass works:	
Mix and furnace rooms, pressing, blowing, tanks, and lehrs	3– 6
Grinding, blowing machines, cutting to size, silvering	5– 10
Fine grinding, polishing, beveling, inspecting, etching, and decorating	6– 12
Glass cutting, inspecting (fine)	10– 50
Glove manufacturing:	
Cutting, pressing, knitting:	
Light goods	5– 10
Dark goods	6– 12
Sorting, stitching, trimming, and inspecting:	
Light goods	6– 12
Dark goods	10– 50

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Gymnasium:	
Main exercising floors	5– 10
Swimming pools	3– 6
Shower rooms	3– 6
Locker rooms	3– 6
Fencing, boxing, wrestling	5– 10
Basketball and indoor baseball	6– 12
Bowling:	
(On alley, runway, and seats)	3– 6
On pins	10– 20
Billiards:	
General	3– 6
On table	10– 20
Racquet, handball, squash, and indoor tennis	10– 20
Skating rinks	4– 8
Halls:	
Passageways in interiors	1 2
Public	3– 6
Hat manufacturing:	
Dyeing, stiffening, braiding, cleaning, and refining:	
Light goods	4– 8
Dark goods	6– 12
Forming, sizing, pouncing, flanging, finishing, ironing:	
Light goods	5– 10
Dark goods	6– 12
Sewing:	
Light goods	6– 12
Dark goods	10– 50
Hospitals:	
Lobbies and reception rooms	3– 6
Corridors	2– 4
Operating tables	50– 100
Wards and private rooms:	
With no local illumination	4– 8
With local illumination	2– 4
Night illumination	0.1– 0.2
Hotels:	
Bedrooms	4– 6
Corridors	1– 2
Dining rooms, lobbies	4– 8
Writing rooms	5– 10
Ice making:	
Engine and compressor rooms	4– 8

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Inspecting:	
Rough	4– 8
Medium	6– 12
Fine	10– 20
Extra fine	15– 50
Jewelry and watch manufacturing	10– 50
Knitting (see Sewing, and Textile Mills)	
Laundries and dry cleaning	5– 10
Lavatories	2– 5
Leather manufacturing:	
Vats	2– 4
Cleaning and tanning, stretching	3– 6
Cutting, fleshing, and stuffing	4– 8
Finishing and scarfing	6– 12
Leather working:	
Pressing and winding:	
Light goods	5– 10
Dark goods	6– 12
Grading, matching, cutting, sewing:	
Light goods	6– 12
Dark goods	10– 20
Libraries:	
Stack rooms	3– 6
Reading rooms:	
With no local illumination	5– 10
With local illumination	3– 6
Locker rooms	2– 4
Lodge rooms	4– 6
Machine shops:	
Rough bench and machine work	4– 8
Medium bench and machine work, ordinary automatic machines, rough grinding, medium buffing, and polishing	6– 12
Fine bench and machine work, fine automatic machines, medium grinding, fine buffing, and polishing	8– 16
Extra-fine bench and machine work, small instrument assembling	10– 50
Markets:	
General:	
With no local illumination	6– 10
With local illumination	3– 6
Meat packing:	
Slaughtering	3– 6
Cleaning, cutting, cooking, grinding, canning, and packing	5– 10

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Milling and grain foods:	
Cleaning, grinding, and rolling	3– 6
Baking and roasting	5– 10
Elevator storage bins	0.1– 1
Flour grading	10– 20
Moving-picture theaters:	
Intermission	2– 4
During pictures	0.1– 0.3
Museums	4– 6
Offices:	
File rooms	3– 6
Desks	8– 10
General, private	6– 10
Vaults:	
Safe	4– 6
Storage	2– 4
Packing:	
Rough	3– 6
Medium	4– 8
Fine	6– 12
Paint manufacturing	4– 10
Paint shops:	
Firing, dipping, and spraying	3– 6
Rubbing, hand painting, and finishing (ordinary)	5– 10
Hand painting and finishing (fine)	6– 12
Hand painting and finishing (extra fine) (automobile bodies, piano cases, etc.)	10– 50
Paper manufacturing:	
Beaters, machine grinding	3– 6
Calendering	4– 8
Finishing, cutting, trimming	6– 12
Paper-box manufacturing:	
Cutting, machine folding, hand folding, pasting and assembling:	
Light	4– 8
Dark	5– 10
Parks (see Streets)	
Pattern shops	4– 8
Photography (see Studio)	
Plating:	
Plating, rough	3– 6
Polishing and burnishing	5– 10
Power houses	4– 6

Table 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Printing industries:	
Matrixing, casting, miscellaneous machines, presses (job and small automatic rotary, flat bed, etc.)	5– 10
Proofreading, lithographing, electrotyping	6– 15
Linotype, monotype, typesetting, composing stone, engraving	10– 50
Railway stations:	
Waiting rooms	2– 4
Ticket offices, etc. (see Offices)	6– 10
Rest rooms, smoking rooms, etc	1– 3
Baggage rooms	3– 6
Concourses	1– 2
Train platforms	0.5– 1
Receiving and shipping	3– 6
Residences	0.5– 8
Restaurants	4– 8
Rinks (skating) indoor	3– 5
Roadways and yard thoroughfares	0.1– 0.5
Rubber-manufacturing products:	
Compounding, mills, fabric preparation, stock cutting, tubing machine, solid-tire operations, mechanical-goods building, vulcanizing	5– 10
Calenders, bead building, pneumatic-tire finishing, trimming, tennis-ball sewing, inspecting	6– 15
Schools:	
Assembly rooms	4– 6
Classrooms, study rooms, offices, libraries	5– 10
Cloak rooms	2– 4
Corridors	2– 4
Drawing rooms	10– 20
Laboratories	8– 12
Manual training	6– 12
Sewing fabrics:	
Light goods, fine	10– 20
Dark goods, fine	20– 50
Shafting, pulleys, and mechanical transmissions	1– 3
Sheet-metal works:	
Miscellaneous machines, ordinary benchwork	5– 10
Punch presses, shears, stamps, welders, spinning, fine benchwork	6– 12
Tin-plate inspection	10– 20
Shoe manufacturing:	
Hand turning, miscellaneous bench- and machinework	5– 10
Inspecting and sorting raw materials, cutting, lasting and welting, stitching:	

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Light goods	6– 12
Dark goods	10– 50
Show windows:	
Light goods	20– 50
Dark goods	30– 75
Signs:	
Outdoor boards:	
Light	10– 30
Dark	20– 50
Soap manufacturing:	
Kettle houses, cutting, soap chip and powder	3– 6
Stamping, wrapping and packing, filling and packing soap powder	4– 8
Steel and iron mills, bar, sheet, and wire products:	
Soaking pits and reheating furnaces	1– 2
Charging and casting floors	2– 4
Muck and heavy rolling, shearing (rough by gage), pickling, and cleaning	3– 6
Automatic machines, rod, light, and cold rolling, wire drawing, shearing (fine by line)	4– 10
Plate inspection	10– 20
Stone crushing and screening:	
Belt-conveyor tubes, main-line shafting spaces, chute rooms, inside of bins	1– 3
Primary breaker rooms, auxiliary breakers under bins	2– 4
Screen rooms	4– 6
Storage and stock rooms:	
Rough, no reading of labels	1– 3
Medium	3– 6
Fine	4– 8
Stores:	
Art	6– 12
Baker	4– 8
Book	4– 8
Butcher	4– 8
Carpet	5– 10
Rug rack	10– 20
China	5– 10
Cigar	6– 12
Clothing	6– 12
Confectionery	4– 8
Decorator	6– 12
Department (see each department)	

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Drugs	4– 8
Dry-goods	5– 10
Florist	4– 8
Furniture	4– 8
Furrier	6– 12
Grocery	4– 8
Haberdashery	6– 12
Hardware	4– 8
Hat	6– 12
Jewelry	6– 12
Leather	5– 10
Main floors	6– 12
Millinery	6– 12
Music	4– 8
Notions, dark	6– 12
Piano	4– 8
Shoes	6– 12
Stationery	4– 8
Streets:	
Business (not including light from windows and signs)	1– 2
Prominent (in residence district)	0.25– 1
Residence	0.05– 0.2
Country roads	0.05– 0.2
Structural-steel fabrication	4– 8
Studios:	
Art and photographic	5– 15
Moving-picture:	
General	4– 6
Sets (photographic daylight)	500–2,000
Sugar grading	10– 20
Telegraph operating	4– 12
Telephone:	
Manual exchanges	4– 6
Automatic exchanges	6– 12
Testing:	
Rough	4– 6
Fine	6– 12
Extra-fine instruments, scales, etc	10– 50
Textile mills:	
Cotton:	
Opening and lapping, carding, drawing-frame slashing	3– 6
Roving, spooling, spinning, drawing in, warping, weaving	5– 10

TABLE 24.—*Continued*

Standards of Desirable Illumination for Various Classes of Service

Industry or Place	Range of Foot-candles
Dyeing	5– 15
Silk:	
Winding, throwing, dyeing	5– 15
Quilling, warping, weaving, and finishing:	
Light goods	5– 10
Dark goods	8– 15
Wool:	
Carding, picking, washing, and combing	3– 6
Twisting and dyeing	4– 8
Drawing in, warping:	
Light goods	4– 8
Dark goods	6– 12
Weaving:	
Light goods	5– 10
Dark goods	8– 16
Knitting machines	6– 12
Theaters:	
Auditoriums	3– 6
Foyers	4– 6
Lobbies	6– 10
Tobacco products:	
Drying, stripping, general	1– 3
Grading, sorting	10– 20
Toilet and wash rooms	2– 5
Trains (see Cars)	
Vessels (see Residences, Storage Rooms, Machine Shops):	
Warehouses	1– 2
Wharves:	
Freight	1– 3
Passenger	2– 5
Woodworking:	
Rough sawing (saw mills), benchwork (rough)	3– 6
Sizing, planing, rough sanding, machine woodworking (medium), benchwork (medium), gluing and veneering, cooperage	5– 10
Machine woodworking (fine), benchwork (fine), fine sanding and finishing	6– 12

Choice of Reflecting Equipment.—Various lighting units are rated in accordance with seven fundamentals, illustrated on the following page. The importance of these criteria differs for different classes of work. It must be emphasized that the relative importance of the various criteria should be carefully weighed with respect to the particular problem at hand. For instance, in an office the criteria would rank in importance: (1) direct glare; (2) reflected glare; (3) shadows; (4) efficiency based upon illumination on horizontal; (5) maintenance; (6) vertical illumination. On the other hand, where lamps are to be hung above a crane in a foundry, the order of importance would be: (1) efficiency based upon illumination on horizontal; (2) vertical illumination; (3) maintenance; (4) shadows; (5) direct glare; (6) reflected glare.

In the chart the best rating given is A+, which denotes the highest degree of excellence, while D, the lowest, indicates that an installation of units so rated in any particular will very likely prove unsatisfactory in an installation where this factor is important. The ratings B and C, while indicating a result not equal to A, are decidedly superior to rating D. In other words, a rating B, C+, or C in certain respects does not disqualify a unit, provided that in the essential requirements of a given location the unit is rated A or B+.

$$\left.\begin{array}{l}A+\\A\\A-\end{array}\right\}\text{Excellent, }\left.\begin{array}{l}B+\\B\\B-\end{array}\right\}\text{Good, }\left.\begin{array}{l}C+\\C\\C-\end{array}\right\}\text{Fair, D Very bad.}$$

The illumination on horizontal surfaces is a prime requisite in offices, drafting rooms, and those shops where the problem is to provide the best illumination for sustained vision of flat surfaces on the horizontal or slightly oblique planes in which papers, books, and other flat objects are usually examined.

The illumination on vertical surfaces of work or machine parts is fully as important as the lighting of the surface in the horizontal plane. In a consideration of the amount of light necessary for factory illumination, the criterion must be the intensity on all working surfaces, whether vertical, horizontal, or oblique.

The favorable appearance of the lighted room refers only to the general or casual effect produced by the complete system, and is not intended to rate the unit as to satisfaction from the standpoint of good vision or freedom from eye fatigue.

Direct glare is the most frequent and serious cause of bad lighting. It results, among other things, from unshaded or inadequately shaded light sources located within the field of vision, or from too great contrast between the bright light source and a dark background or adjacent surfaces. Glare should be avoided by the use of proper reflecting and diffusing equipment.

Reflected glare from polished working surfaces is particularly annoying because of the necessity of directing the eyes toward those surfaces, and, further, because the eyes are by nature especially sensitive to light rays from below. The harmful effects of this specular reflection can be minimized by properly shielding from below or diffusing the source.

Shadows, that is, differences in brightness of surfaces, are essential in observing objects in their three dimensions, but are of little or no value in the observation of flat surfaces. Where shadows are desirable, they should be soft and luminous, not so sharp and dense as to confuse the object with its shadow.

Maintenance depends upon contour of reflector, construction of fixture, and condition of ceiling. The rating is based upon the likelihood of breakage, the labor involved in maintaining the units at comparable degrees of efficiency, and indication given of need of cleaning.

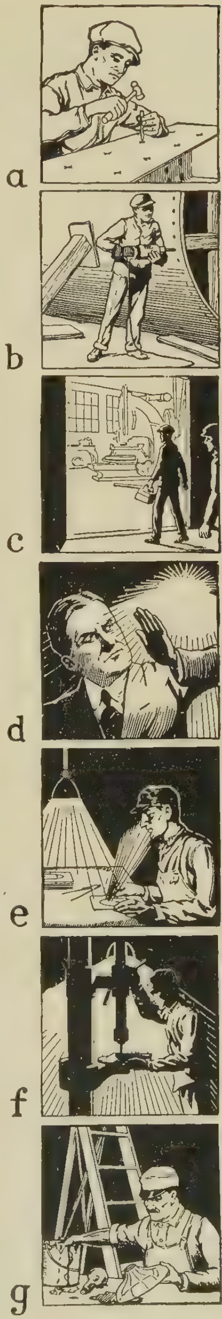


Fig. 105.

TABLE 25

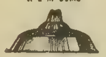
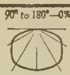
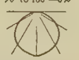
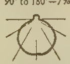
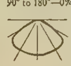
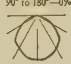
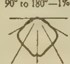
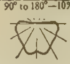
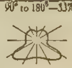
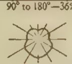
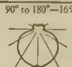
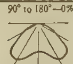
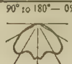
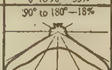
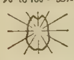
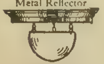
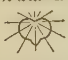
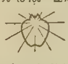
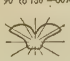
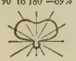
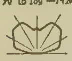
A GUIDE TO THE SELECTION OF REFLECTING EQUIPMENT									
LIGHTING UNIT			EFFICIENCY BASED UPON		FAVORABLE APPEARANCE OF LIGHTED ROOM	DIRECT GLARE	REFLECTED GLARE	SHADOWS	MAINTENANCE
			ILLUMINATION ON HORIZONTAL	ILLUMINATION ON VERTICAL					
DIRECT LIGHTING PORCELAIN ENAMEL REFLECTORS									
1	R L M DOME  Clear Lamp	90° to 180°—0%  0° to 90°—76%	A+	B+	C+	C	D	C+	A+
2	R L M DOME Bowl-Enameled Lamp	90° to 180°—0%  0° to 90°—66%	A−	B	B	B+	B	B+	A−
3	GLASSTEEL DIFFUSER 	90° to 180°—7%  0° to 90°—60%	B+	B	A−	A−	B+	A−	B+
4	DEEP BOWL  Clear Lamp	90° to 180°—0%  0° to 90°—65%	B+	B−	C	C+	D	C	A
5	DEEP BOWL Bowl-Enameled Lamp	90° to 180°—0%  0° to 90°—58%	B	C+	C	B	C+	C+	B+
6	FLAT CONE Shielding Band  Clear Lamp	90° to 180°—1%  0° to 90°—54%	B	C+	C+	C+	D	C	B+
7	FLAT CONE  Clear Lamp	90° to 180°—10%  0° to 90°—74%	B	B	C	D	D	C	A+
DIRECT LIGHTING OPEN GLASS REFLECTORS									
8	LIGHT DENSITY OPAL  Clear Lamp	90° to 180°—33%  0° to 90°—54%	B+	B	B+	C+	D	B−	B
9	LIGHT DENSITY OPAL Bowl-Enameled Lamp	90° to 180°—36%  0° to 90°—45%	B	B−	A−	B−	B−	B+	B−
10	DENSE OPAL  Clear Lamp	90° to 180°—15%  0° to 90°—67%	A+	B+	B+	B	D	C+	A−
11	DENSE OPAL Bowl-Enameled Lamp	90° to 180°—16%  0° to 90°—60%	B+	B−	A−	B+	B−	B	B
12	MIRRORED GLASS  Clear Lamp	90° to 180°—0%  0° to 90°—68%	A	B	C	C+	D	C	A−
13	MIRRORED GLASS Bowl-Enameled Lamp	90° to 180°— 0%  0° to 90°—55%	B	C+	C	B−	C	C+	B−
14	PRISMATIC INDUSTRIAL  Clear Lamp	90° to 180°—18%  10° to 90°—73%	A+	A−	B+	C+	D	C+	B−

TABLE 25.—*Continued*

A GUIDE TO THE SELECTION OF REFLECTING EQUIPMENT

	Lighting Unit		Efficiency Based upon Illumination on Horizontal	Efficiency Based upon Illumination on Vertical	Favorable Appearance of Lighted Room	Direct Glare	Reflected Glare	Shadows	Maintenance
	DIRECT LIGHTING ENCLOSING AND SEMI-ENCLOSING UNITS								
15	DIFFUSING GLOBE Light Opal 	90° to 180°—35%  0° to 90°—40%	B−	B−	A	B−	B	B+	B+
16	ONE-PIECE OPAL Flattened, Reflecting Top 	90° to 180°—35%  0° to 90°—45%	B	B	A	B	B	A−	A−
17	PRISMATIC ENCLOSING 	90° to 180°—27%  0° to 90°—59%	B+	B	A	B	B−	B+	B
18	SEMI-ENCLOSING Metal Reflector 	90° to 180°—20%  0° to 90°—56%	B	B	A	B	B	B+	B−
19	SEMI-ENCLOSING Compo Reflector 	90° to 180°—13%  0° to 90°—60%	B	B	A	A	A−	A−	C+
20	TWO-PIECE GLASS Opal Refl and Enam Bowl 	90° to 180°—12%  0° to 90°—53%	B	B	A	B+	B+	A−	B
21	ONE-PIECE GLASS Enameled Refl and Bowl 	90° to 180°—22%  0° to 90°—50%	B	B	A	B+	B	A−	A−
	SEMI-INDIRECT AND INDIRECT LIGHTING UNITS								
22	LIGHT OPAL 	90° to 180°—60%  0° to 90°—25%	B−	C+	A	B+	B+	A−	C
23	DENSE OPAL (or Light Opal and Bowl-Enameled Lamp)	90° to 180°—70%  0° to 90°—10%	C+	C	A	A+	A	A+	C
24	ENAMELED METAL REFLECTOR Opal Glass Bottom 	90° to 180°—69%  0° to 90°—6%	C+	C	A	A+	A	A+	C
25	PRISMATIC ENCLOSED 	90° to 180°—57%  0° to 90°—26%	B−	C+	A	A−	A−	A−	B
26	CLEAR TOP ENCLOSED Enameled Glass 	90° to 180°—54%  0° to 90°—21%	C+	C	A	A+	A	A	B
27	MIRRORED INDIRECT 	90° to 180°—80%  0° to 90°—0%	C+	C	B+*	A+	A	A+	C
28	ENAMELED METAL INDIRECT 	90° to 180°—74%  0° to 90°—0%	C	C	B+	A+	A	A+	C

*For Luminous Bowl Type Rate A.

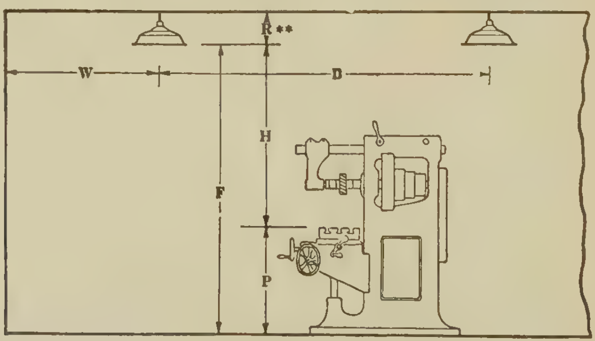
Table 26*a*

Spacing—Mounting Height

Direct-lighting Units, Including Semi-enclosing and Totally Enclosing Units, Nos. 1 to 21

Mounting height of unit		Permissible distance between outlets	Permissible distance between outlets and sidewalls	
Above plane of work (*H*)	Above floor[1] (*F*)	(*D*)	In usual locations where aisles and storage are next to wall (*W*)	In offices or where work benches are next to wall (*W*)
4	6½	6	3	2
5	7½	7½	3½	2½
6	8½	9	4½	3
7	9½	10½	5	3½
8	10½	12	6	4
9	11½	13½	6½	4½
10	12½	15	7½	5
11	13½	16½	8	5½
12	14½	18	9	6
13	15½	19½	9½	6½
14	16½	21	10½	7
15	17½	22½	11	7½
16	18½	24	12	8
18	20½	27	13½	9
20	22½	30	15	10
22	24½	33	16½	11
24	26½	36	18	12
27	29½	40½	20	13½
30	32½	45	22½	15
35	37½	52½	26	17½
40	42½	60	30	20

[1] Plane of work (*P*) assumed to be 2½ ft. above floor. When the plane of work is higher or lower than 2½ ft. above floor, neglect column (*F*) and work from column (*H*).



**Minimum allowance for (R) usually 1 ft.

Fig. 106.

TABLE 26b

Spacing—Mounting Height

Semi and Totally Indirect-lighting Units, Nos. 22 to 28

Ceiling height		Permissible spacing distance between outlets	Permissible distance between outlet and sidewalls		Suspension distance ceiling to top of reflector[2]
Above plane of work (H)	Above floor[1] (C)	(D)	In usual locations where aisles and storage are next to wall (W)	In offices or where work benches are next to wall (W)	(R)
5	7½	7½	3½	2½	1¼
6	8½	9	4½	3	1½
7	9½	10½	5	3½	1¾
8	10½	12	6	4	2
9	11½	13½	6½	4½	2¼
10	12½	15	7½	5	2½
11	13½	16½	8	5½	2¾
12	14½	18	9	6	3
13	15½	19½	9½	6½	3¼
14	16½	21	10½	7	3½
15	17½	22½	11	7½	3¾
16	18½	24	12	8	4
18	20½	27	13½	9	4½
21	23½	31½	15½	10½	5¼
24	26½	36	18	12	6
27	29½	40½	20	13½	6¾
30	32½	45	22½	15	7½
35	37½	52½	26	17½	8¾
40	42½	60	30	20	10

[1] Plane of work (P) assumed to be 2½ ft. above floor. When the plane of work is higher or lower than 2½ ft. above floor, neglect column (C) and work from column (H).

[2] Suspension distances (R) in table are based on best distribution of light and efficiency of utilization for standard units. In some installations other considerations may require a different suspension distance.

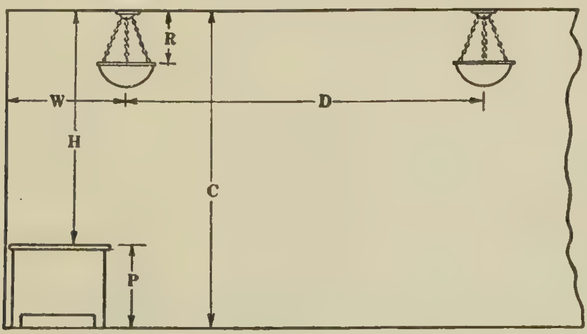


FIG. 107.

Table 27

Coefficients of Utilization

Find *Room Index* from Table 28

Direct-lighting Porcelain Enamel Reflectors

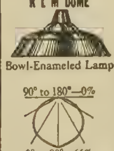
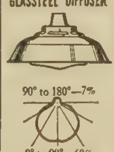
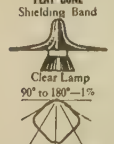
	COLOR REFLECTION FACTOR	CEILING	VERY LIGHT (70%)			FAIRLY LIGHT (50%)			FAIRLY DARK (30%)	
		WALLS	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY DARK (30%)	VERY DARK (10%)
	REFLECTOR TYPE	ROOM INDEX	COEFFICIENTS OF UTILIZATION							
1	R L M DOME  Clear Lamp 90° to 180°—0% 0° to 90°—76%	0.6	.34	.29	.24	.34	.29	.24	.28	.24
		0.8	.42	.38	.34	.42	.37	.33	.37	.33
		1.0	.46	.43	.39	.45	.42	.39	.42	.39
		1.25	.50	.47	.43	.49	.46	.43	.45	.42
		1.5	.53	.50	.46	.52	.49	.46	.48	.45
		2.0	.58	.55	.51	.57	.54	.51	.53	.51
		2.5	.62	.59	.56	.61	.58	.56	.58	.56
		3.0	.64	.61	.58	.63	.60	.58	.60	.58
		4.0	.67	.65	.63	.66	.64	.62	.63	.61
		5.0	.69	.67	.65	.67	.66	.64	.65	.63
2	R L M DOME  Bowl-Enameled Lamp 90° to 180°—0% 0° to 90°—66%	0.6	.32	.28	.25	.32	.28	.25	.27	.25
		0.8	.40	.36	.34	.39	.35	.33	.35	.33
		1.0	.43	.39	.37	.42	.39	.37	.39	.37
		1.25	.46	.43	.41	.45	.43	.41	.43	.41
		1.5	.48	.45	.43	.47	.45	.43	.45	.43
		2.0	.52	.50	.48	.51	.49	.47	.49	.47
		2.5	.56	.54	.52	.55	.53	.51	.53	.51
		3.0	.57	.55	.53	.56	.54	.52	.54	.52
		4.0	.60	.58	.56	.59	.57	.55	.57	.55
		5.0	.61	.59	.57	.60	.58	.57	.58	.56
3	GLASSTEEL DIFFUSER  90° to 180°—7% 0° to 90°—60%	0.6	.29	.25	.21	.28	.24	.21	.23	.21
		0.8	.36	.32	.29	.35	.31	.28	.31	.28
		1.0	.39	.36	.33	.38	.35	.33	.34	.32
		1.25	.42	.39	.36	.41	.38	.36	.37	.35
		1.5	.45	.42	.39	.43	.40	.38	.39	.38
		2.0	.49	.46	.43	.48	.45	.43	.44	.42
		2.5	.53	.50	.47	.51	.49	.47	.47	.46
		3.0	.54	.52	.49	.52	.50	.49	.49	.47
		4.0	.57	.55	.53	.55	.53	.51	.51	.50
		5.0	.58	.56	.54	.56	.54	.53	.52	.51
4	DEEP BOWL  Clear Lamp 90° to 180°—0% 0° to 90°—65%	0.6	.31	.26	.23	.30	.26	.23	.25	.23
		0.8	.38	.34	.31	.37	.34	.31	.33	.31
		1.0	.41	.38	.35	.41	.38	.35	.37	.35
		1.25	.44	.41	.38	.44	.41	.38	.40	.38
		1.5	.47	.44	.41	.46	.43	.41	.43	.41
		2.0	.51	.48	.45	.50	.47	.45	.47	.45
		2.5	.54	.51	.49	.53	.51	.49	.51	.49
		3.0	.56	.54	.51	.55	.53	.51	.53	.51
		4.0	.58	.56	.54	.57	.55	.54	.55	.53
		5.0	.60	.58	.56	.58	.57	.55	.56	.55
5	DEEP BOWL  Bowl-Enameled Lamp 90° to 180°—0% 0° to 90°—58%	0.6	.29	.26	.23	.29	.26	.23	.25	.23
		0.8	.35	.33	.31	.35	.32	.30	.32	.30
		1.0	.38	.36	.34	.38	.36	.34	.35	.34
		1.25	.41	.39	.37	.41	.39	.37	.38	.37
		1.5	.44	.41	.39	.43	.41	.39	.40	.39
		2.0	.47	.45	.43	.46	.44	.43	.43	.43
		2.5	.50	.48	.46	.49	.47	.46	.46	.46
		3.0	.51	.49	.47	.50	.48	.47	.47	.47
		4.0	.53	.51	.50	.52	.50	.49	.49	.49
		5.0	.54	.52	.51	.53	.51	.50	.50	.49
6	FLAT CONE Shielding Band  Clear Lamp 90° to 180°—1% 0° to 90°—64%	0.6	.27	.23	.21	.26	.23	.21	.23	.21
		0.8	.32	.30	.28	.32	.29	.27	.29	.27
		1.0	.35	.33	.31	.35	.33	.31	.32	.31
		1.25	.38	.36	.34	.37	.36	.34	.35	.34
		1.5	.40	.38	.36	.39	.37	.36	.37	.36
		2.0	.43	41	.39	.42	.41	.39	.40	.39
		2.5	.46	44	.42	.45	.43	.42	.43	.42
		3.0	.47	.45	.43	.46	.44	.43	.44	.43
		4.0	.49	.47	.46	.48	.46	.45	.46	.45
		5.0	.50	.48	.47	.49	.47	.46	.47	.46
7	FLAT CONE  Clear Lamp 90° to 180°—10% 0° to 90°—74%	0.6	.26	.20	.16	.26	.19	.16	.19	.16
		0.8	.32	.26	.22	.32	.26	.22	.26	.22
		1.0	.36	.30	.26	.36	.30	.26	.30	.26
		1.25	.41	.35	.30	.39	.34	.30	.33	.30
		1.5	.44	.38	.33	.42	.37	.33	.36	.33
		2.0	.50	44	.38	.48	.43	.38	.42	.38
		2.5	.54	.48	.42	.52	.47	.42	.46	.42
		3.0	.57	.51	.46	.55	.50	.45	.49	.45
		4.0	.62	.56	.51	.60	.54	.50	.53	.50
		5.0	.65	.60	.54	.62	.56	.53	.55	.53

TABLE 27.—*Continued*

Coefficients of Utilization

Find *Room Index* from Table 28

Direct-lighting Open Glass Reflectors

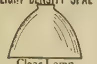
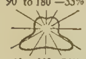
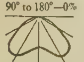
	COLOR REFLECTION FACTOR — CEILING		VERY LIGHT (70%)			FAIRLY LIGHT (50%)			FAIRLY DARK (30%)	
	WALLS		FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY DARK (30%)	VERY DARK (10%)
	REFLECTOR TYPE	ROOM INDEX	COEFFICIENTS OF UTILIZATION							
8	LIGHT DENSITY OPAL  Clear Lamp	0.6	.26	.21	.17	.24	.19	.16	.18	.15
		0.8	.32	.27	.23	.30	.25	.22	.24	.21
		1.0	.36	.31	.27	.34	.29	.26	.27	.24
		1.25	.40	.35	.31	.37	.32	.29	.30	.27
		1.5	.44	.38	.34	.40	.35	.32	.32	.30
	90° to 180°—33%  0° to 90°—54%	2.0	.49	.44	.39	.45	.40	.37	.37	.34
		2.5	.53	.48	.44	.49	.44	.41	.40	.38
		3.0	.56	.51	.47	.51	.46	.43	.42	.40
		4.0	.60	.55	.51	.55	.50	.47	.46	.44
		5.0	.62	.58	.54	.57	.53	.50	.48	.46
9	LIGHT DENSITY OPAL  Bowl-Enameled Lamp	0.6	.22	.17	.14	.20	.16	.13	.14	.12
		0.8	.27	.22	.19	.25	.21	.18	.19	.16
		1.0	.31	.26	.23	.28	.24	.21	.22	.19
		1.25	.35	.30	.26	.31	.27	.24	.24	.22
		1.5	.38	.33	.29	.34	.30	.26	.27	.24
	90° to 180°—36%  0° to 90°—45%	2.0	.43	.38	.34	.38	.34	.31	.30	.28
		2.5	.47	.42	.38	.42	.38	.34	.34	.31
		3.0	.49	.44	.40	.44	.40	.37	.36	.33
		4.0	.53	.49	.45	.48	.44	.41	.39	.37
		5.0	.56	.52	.43	.50	.46	.43	.40	.39
10	DENSE OPAL  Clear Lamp	0.6	.32	.27	.23	.31	.26	.22	.25	.22
		0.8	.40	.35	.31	.38	.34	.31	.33	.30
		1.0	.44	.39	.36	.42	.38	.35	.37	.35
		1.25	.47	.43	.40	.46	.42	.39	.40	.38
		1.5	.51	.47	.43	.49	.45	.42	.43	.41
	90° to 180°—15%  0° to 90°—67%	2.0	.56	.52	.48	.54	.50	.47	.48	.46
		2.5	.60	.56	.53	.57	.54	.52	.52	.50
		3.0	.63	.59	.55	.60	.56	.54	.54	.52
		4.0	.66	.63	.60	.63	.60	.58	.57	.55
		5.0	.67	.65	.62	.65	.61	.59	.59	.57
11	DENSE OPAL  Bowl-Enameled Lamp	0.6	.29	.24	.20	.28	.23	.20	.22	.20
		0.8	.35	.31	.28	.34	.30	.27	.29	.27
		1.0	.39	.35	.32	.38	.34	.32	.33	.31
		1.25	.43	.39	.36	.41	.38	.35	.36	.34
		1.5	.46	.42	.38	.44	.40	.37	.38	.36
	90° to 180°—16%  0° to 90°—60%	2.0	.51	.47	.44	.48	.45	.42	.43	.41
		2.5	.55	.51	.48	.52	.49	.46	.47	.45
		3.0	.57	.54	.50	.54	.51	.48	.48	.46
		4.0	.60	.57	.54	.57	.54	.52	.51	.50
		5.0	.62	.59	.56	.58	.56	.54	.53	.52
12	MIRRORED GLASS  Clear Lamp	0.6	.32	.27	.24	.31	.27	.24	.27	.24
		0.8	.39	.35	.32	.39	.35	.32	.35	.32
		1.0	.43	.39	.37	.42	.39	.37	.39	.37
		1.25	.46	.43	.40	.46	.43	.40	.42	.40
		1.5	.49	.46	.43	.48	.45	.43	.45	.43
	90° to 180°—0%  0° to 90°—68%	2.0	.53	.50	.48	.52	.50	.48	.49	.48
		2.5	.57	.54	.52	.56	.54	.52	.53	.52
		3.0	.58	.56	.54	.57	.55	.54	.54	.53
		4.0	.61	.59	.57	.60	.58	.56	.57	.56
		5.0	.63	.61	.58	.61	.59	.58	.58	.57
13	MIRRORED GLASS  Bowl-Enameled Lamp	0.6	.26	.22	.19	.25	.22	.19	.21	.19
		0.8	.32	.29	.26	.31	.28	.26	.28	.26
		1.0	.35	.32	.30	.34	.32	.30	.31	.30
		1.25	.38	.35	.33	.37	.35	.33	.34	.33
		1.5	.40	.37	.35	.39	.37	.35	.36	.35
	90° to 180°—0%  0° to 90°—55%	2.0	.43	.41	.39	.42	.40	.39	.40	.39
		2.5	.46	.44	.42	.45	.43	.42	.43	.42
		3.0	.47	.46	.44	.46	.45	.44	.44	.43
		4.0	.49	.48	.46	.48	.47	.46	.46	.45
		5.0	.50	.49	.47	.49	.48	.47	.47	.46
14	PRISMATIC INDUSTRIAL  Clear Lamp	0.6	.33	.26	.21	.31	.25	.21	.24	.20
		0.8	.41	.35	.30	.39	.33	.29	.32	.29
		1.0	.45	.40	.35	.43	.39	.34	.37	.33
		1.25	.50	.44	.39	.47	.42	.38	.40	.37
		1.5	.52	.48	.43	.50	.45	.42	.43	.40
	90° to 180°—18%  0° to 90°—73%	2.0	.58	.54	.49	.56	.51	.47	.49	.46
		2.5	.63	.59	.54	.60	.56	.53	.54	.51
		3.0	.66	.62	.58	.63	.59	.56	.56	.54
		4.0	.71	.67	.63	.67	.63	.61	.60	.58
		5.0	.73	.69	.66	.69	.65	.63	.62	.60

TABLE 27.—*Continued*

Coefficients of Utilization

Find *Room Index* from Table 28

Direct-lighting Enclosing and Semi-enclosing Units

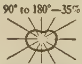
	Color Reflection Factor	Ceiling	Very Light (70%)			Fairly Light (50%)			Fairly Dark (30%)	
		Walls	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Light (50%)	Fairly Dark (30%)	Very Dark (10%)	Fairly Dark (30%)	Very Dark (10%)
	Reflector Type	Room Index	**COEFFICIENTS OF UTILIZATION**							
15	DIFFUSING GLOBE Light Opal	0.6	.18	.13	.10	.16	.12	.10	.10	.09
		0.8	.22	.17	.14	.20	.16	.13	.14	.12
		1.0	.26	.21	.18	.23	.19	.16	.17	.14
		1.25	.29	.24	.21	.26	.22	.19	.19	.16
		1.5	.32	.27	.23	.29	.24	.21	.22	.19
	90° to 180°—35%	2.0	.37	.32	.28	.32	23	.25	.25	.22
		2.5	.40	.35	.31	.35	.31	.28	.28	.25
		3.0	.43	.38	.34	.38	.33	.30	.30	.27
		4.0	.47	.42	.38	.41	.37	.34	.33	.31
	0° to 90°—40%	5.0	.49	.45	.41	.43	.39	.36	.34	.33
16	ONE-PIECE OPAL Flattened Reflecting Top	0.6	.22	.17	.14	.20	.16	.13	.14	.12
		0.8	.27	.22	.19	.25	.21	.18	.19	.17
		1.0	.31	.26	.23	.28	.24	.21	.22	.19
		1.25	.35	.30	.26	.31	.27	.24	.25	.22
		1.5	.38	33	.29	.34	.30	.27	.27	.24
	90° to 180°—35%	2.0	.42	.38	.33	.38	.34	.31	.31	.28
		2.5	.46	.41	.37	.41	.37	.34	.34	.31
		3.0	.49	.45	.40	.43	.39	.36	.36	.33
		4.0	.53	.48	.44	.47	.43	.40	.38	.36
	0° to 90°—45%	5.0	.55	.51	.47	.49	.45	.42	.40	.38
17	PRISMATIC ENCLOSING	0.6	.28	.22	.18	.26	.21	.17	.19	.16
		0.8	.35	.29	.25	.33	.28	.24	.26	.23
		1.0	.38	.33	.29	.36	.32	.28	.30	.27
		1.25	.43	.37	.33	.40	.35	.31	.33	.30
		1.5	.46	.41	.36	.43	.38	.34	.35	.33
	90° to 180°—27%	2.0	.51	.46	.42	.47	.43	.40	.40	.38
		2.5	.55	.51	.46	.51	.47	.44	.44	.42
		3.0	.58	.54	.50	.54	.50	.47	.46	.44
		4.0	.62	.58	.55	.57	.54	.51	.50	.48
	0° to 90°—59%	5.0	.65	.61	.57	.60	.56	.53	.52	50
18	SEMI-ENCLOSING Metal Reflector	0.6	.22	.17	.13	.21	.16	.13	.15	.13
		0.8	.28	.22	.19	.26	.21	.18	.21	.18
		1.0	.31	.26	.23	.30	.25	.22	.24	.21
		1.25	.35	.30	.26	.32	.28	.25	.27	.24
		1.5	.38	.33	.28	.36	.31	.27	.30	.26
	90° to 180°—20%	2.0	.43	.38	.33	.40	.36	.32	.34	.30
		2.5	.46	.41	.37	.44	.39	.36	.37	.34
		3.0	.49	.44	.40	.46	.42	.38	.40	.37
		4.0	.54	.49	.44	.50	.45	.42	.43	.40
	0° to 90°—56%	5.0	.56	.51	.47	.52	.47	.45	.44	.43
19	SEMI-ENCLOSING Compo Reflector	0.6	.24	.18	.14	.23	.18	.14	.17	.14
		0.8	.30	.24	.21	.29	.24	.20	.23	.20
		1.0	.33	.28	.25	.32	.28	.24	.27	24
		1.25	.37	.32	.28	.35	.31	.27	.30	.27
		1.5	.39	.35	.31	.38	.34	.30	.32	.29
	90° to 180°—13%	2.0	.44	.40	.35	.42	.38	.34	.37	.34
		2.5	.48	.44	.39	.46	.42	.38	.41	.38
		3.0	.50	.46	.42	.48	.44	.41	.43	.40
		4.0	.55	.51	.47	.53	.49	.45	.46	.44
	0° to 90°—60%	5.0	.57	.53	.49	.54	.50	.47	.48	.46
20	TWO-PIECE GLASS Opal Reflector and Enameled Bowl	0.6	.22	.17	.14	.21	.17	.14	.16	.14
		0.8	.27	.23	.20	.26	.22	.19	.22	.19
		1.0	.30	.26	.23	.29	.26	.23	.25	.22
		1.25	.33	.29	.26	.32	.28	.26	.29	.25
		1.5	.36	.32	.29	.35	.31	.28	.31	.27
	90° to 180°—12%	2.0	.41	.37	.33	.39	.35	.32	.34	.31
		2.5	.44	.40	.36	.42	.38	.35	.37	.35
		3.0	.46	.42	.38	.43	.40	.37	.39	.37
		4.0	.49	.45	.42	.47	.43	.41	.42	.40
	0° to 90°—53%	5.0	.51	.48	.44	.48	.45	.43	.43	.41
21	ONE-PIECE GLASS Enameled Reflector and Bowl	0.6	.22	.17	.14	.21	.16	.14	.15	.14
		0.8	.27	.23	.20	.26	.22	.19	.20	.18
		1.0	.30	.26	.23	.29	.25	.22	.23	.21
		1.25	.34	.30	.26	.32	.28	.25	.26	.24
		1.5	.37	.33	.29	.34	.30	.27	.28	.26
	90° to 180°—22%	2.0	.41	.37	.33	.38	.34	.31	.32	.30
		2.5	.44	.40	.36	.41	.38	.35	.35	.33
		3.0	.47	.43	.39	.43	.40	.37	.37	.35
		4.0	.51	.47	.43	.47	.44	.41	.41	.39
	0° to 90°—50%	5.0	.53	.49	.45	.48	.45	.42	.42	.40

TABLE 27.—*Continued*

Coefficients of Utilization

Find *Room Index* from Table 28

Semi-indirect and Indirect-lighting Units

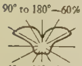
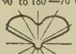
	COLOR REFLECTION FACTOR / REFLECTOR TYPE	CEILING / WALLS / ROOM INDEX	VERY LIGHT (70%)			FAIRLY LIGHT (50%)			FAIRLY DARK (30%)	
			FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY LIGHT (50%)	FAIRLY DARK (30%)	VERY DARK (10%)	FAIRLY DARK (30%)	VERY DARK (10%)
			COEFFICIENTS OF UTILIZATION							
22	LIGHT OPAL 	0.6	.18	.14	.11	.15	.12	.09	.09	.07
		0.8	.22	.18	.15	.19	.15	.12	.12	.10
		1.0	.26	.22	.18	.22	.18	.15	.14	.12
		1.25	.30	.25	.22	.25	.21	.18	.16	.14
		1.5	.33	.28	.24	.27	.23	.20	.18	.16
	90° to 180°—60% 	2.0	.38	.33	.29	.31	.27	.24	.21	.19
		2.5	.41	.36	.32	.34	.30	.27	.24	.22
		3.0	.44	.39	.35	.36	.32	.29	.25	.23
		4.0	49	.44	.40	.40	.36	.33	.28	.26
	0° to 90°—25%	5.0	.51	.46	.42	.42	.38	.35	.29	.28
23	DENSE OPAL (or Light Opal and Bowl-enameled Lamp) 	0.6	.16	.13	.11	.12	.10	.08	.07	.06
		0.8	.20	.17	.15	.16	.13	.11	.09	.08
		1.0	.23	.20	.17	.18	.15	.13	.10	.09
		1.25	.27	.23	.20	.21	.18	.16	.12	.11
		1.5	.29	.26	.22	.23	.19	.17	.13	.12
	90° to 180°—70% 	2.0	.33	.29	.26	.26	.22	.20	.15	.14
		2.5	.36	.32	.29	.28	.25	.23	.17	.16
		3.0	.39	.35	.32	.29	.27	.25	.18	.17
		4.0	.43	.39	.36	.32	.30	.28	.20	.19
	0° to 90°—10%	5.0	.45	.41	.38	.34	.32	.30	.22	.20
24	ENAMELED METAL REFLECTOR Opal Glass Bottom 	0.6	.16	.13	.11	.12	.10	.08	.07	.06
		0.8	.19	.16	.14	.15	.13	.11	.08	.08
		1.0	.22	.19	.17	.17	.15	.13	.10	.09
		1.25	.25	.22	.19	.20	.17	.15	.11	.10
		1.5	.27	.24	.21	.21	.18	.16	.12	.11
	90° to 180°—69% 	2.0	.31	.28	.25	.24	.21	.19	.14	.13
		2.5	.34	.31	.28	.25	.23	.22	.15	.15
		3.0	.36	.33	.31	.27	.25	.23	.16	.15
		4.0	.40	.37	.34	.29	.28	.26	.18	.17
	0° to 90°—6%	5.0	.41	.38	.37	.31	.29	.28	.19	.18
25	PRISMATIC ENCLOSED 	0.6	.19	.15	.12	.16	.13	.10	.10	.09
		0.8	.24	.20	.17	.20	.17	.14	.14	.12
		1.0	.27	.23	.20	.23	.19	.17	.16	.14
		1.25	.31	.27	.23	.26	.22	.20	.18	.16
		1.5	.34	.29	.25	.28	.24	.22	.20	.18
	90° to 180°—57% 	2.0	.38	.34	.30	.32	.28	.25	.22	.20
		2.5	.41	.37	.34	.34	.31	.28	.25	.23
		3.0	.44	.40	.36	.36	.33	.30	.26	.24
		4.0	.48	.44	.41	.40	.36	.34	.29	.27
	0° to 90°—26%	5.0	.50	.46	.43	.42	.38	.36	.30	.29
26	CLEAR TOP ENCLOSED Enameled Glass 	0.6	.16	.12	.10	.13	.10	.08	.07	.06
		0.8	.20	.16	.13	.17	.13	.11	.10	.09
		1.0	.23	.19	.16	.19	.15	.13	.12	.10
		1.25	.26	.22	.19	.21	.18	.15	.14	.12
		1.5	.29	.25	.21	.24	.20	.17	.15	.13
	90° to 180°—54% 	2.0	.32	.28	.25	.26	.23	.20	.18	.16
		2.5	.36	.31	.28	.29	.26	.23	.20	.18
		3.0	.38	.34	.31	.31	.28	.25	.22	.20
		4.0	.42	.38	.35	.34	.31	.29	.24	.22
	0° to 90°—21%	5.0	.44	.40	.37	.36	.33	.31	.25	.24
27	MIRRORED INDIRECT 	0.6	.15	.12	.10	.11	.09	.07	.05	.04
		0.8	.18	.15	.13	.13	.11	.09	.07	.06
		1.0	.22	.19	.16	.15	.13	.11	.08	.07
		1.25	.25	.22	.19	.18	.15	.13	.09	.08
		1.5	.27	.24	.21	.20	.17	.15	.10	.09
	90° to 180°—80% 	2.0	.30	.27	.25	.22	.19	.17	.11	.10
		2.5	.34	.31	.28	.24	.22	.20	.13	.12
		3.0	.36	.33	.30	.26	.24	.22	.14	.13
		4.0	.40	.37	.34	.28	.26	.24	.15	.14
	0° to 90°—0%	5.0	.42	.39	.37	.30	.28	.26	.17	.15
28	ENAMELED METAL INDIRECT 	0.6	.14	.11	.10	.10	.08	.07	.04	.04
		0.8	.17	.14	.13	.13	.10	.09	.06	.05
		1.0	.20	.17	.15	.14	.12	.10	.07	.06
		1.25	.23	.20	.17	.17	.14	.13	.08	.07
		1.5	.25	.22	.19	.18	.15	.14	.09	.08
	90° to 180°—74% 	2.0	.28	.25	.23	.21	.18	.16	.10	.10
		2.5	.31	.28	.26	.22	.20	.18	.12	.11
		3.0	.33	.30	.28	.24	.22	.20	.13	.12
		4.0	.37	.34	.32	.26	.24	.22	.14	.13
	0° to 90°—0%	5.0	.39	.36	.34	.28	.26	.24	.15	.14

Table 28

Room Index[1]

For Finding Coefficient of Utilization from Table 27

Direct Lighting-SOURCES 4 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8	1.0	1.25	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
10	1.25	1.25	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
12	1.25	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
14	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
16	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
18	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
20	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
24	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
30	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
35	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
40	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
50	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
60	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
70	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
80	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
100	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
120	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Semi and Indirect Lighting-CEILING 6 FEET ABOVE WORK PLANE

[1] Since the value of the room index depends on the relation of the length and the width of the room and the height of the light source above the working plane, it follows that these tables can be extended to multiples of these three dimensions from which they are constructed. Thus the room index for rooms 20 by 30, 40 by 60, or 60 by 120 would be the same if the light sources were placed 4, 8, and 12 ft., respectively, above the working plane.

TABLE 28.—*Continued*

Room Index

For Finding Coefficient of Utilization from Table 27

Direct Lighting-SOURCES 5 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
10	1.0	1.0	1.0	1.25	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
12	1.0	1.25	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
14	1.0	1.25	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
16	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
18	1.25	1.25	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
20	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
24	1.25	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
30	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
35	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
40	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
50	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
60	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
70	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
80	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
100	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
120	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5 0

Semi and Indirect Lighting-CEILING $7\frac{1}{2}$ FEET ABOVE WORK PLANE

Direct Lighting-SOURCES 6 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8	0.8	0 8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1 25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
10	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1 5	1.5	1.5
12	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1 5	1.5	1 5	1.5	1.5	1.5	1.5	1.5
14	1.0	1.0	1.25	1.25	1.25	1 25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
16	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
18	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
24	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
30	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
35	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
40	1 5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
50	1.5	1.5	2.0	2.0	2.0	2.0	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
60	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
70	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
80	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
100	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
120	1.5	1.5	2 0	2.0	2.0	2.5	2.5	3.0	3.0	4 0	4.0	5.0	5 0	5.0	5.0	5.0	5.0	5.0	5 0

Semi and Indirect Lighting-CEILING 9 FEET ABOVE WORK PLANE

TABLE 28.—*Continued*

Room Index

For Finding Coefficient of Utilization from Table 27

Direct Lighting-SOURCES 7 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10	0.6	0.8	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
12	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
14	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
16	0.8	0.8	1.0	1.25	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
18	0.8	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20	1.0	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
24	1.0	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
30	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0
35	1.0	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
40	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
50	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
60	1.25	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
70	1.25	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
80	1.25	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
100	1.25	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
120	1.25	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Semi and Indirect Lighting-CEILING $10\frac{1}{2}$ FEET ABOVE WORK PLANE

Direct Lighting-SOURCES 9 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
14	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5
16	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
18	0.6	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
20	0.6	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0
24	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
30	0.8	1.0	1.0	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5
35	0.8	1.0	1.0	1.25	1.25	1.25	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
40	1.0	1.0	1.0	1.25	1.25	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
50	1.0	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
60	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0
70	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
80	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0	4.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0
100	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0
120	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0

Semi and Indirect Lighting-CEILING $13\frac{1}{2}$ FEET ABOVE WORK PLANE

TABLE 28.—*Continued*

Room Index

For Finding Coefficient of Utilization from Table 27

Direct Lighting-SOURCES 16 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8									0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
10								0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8
12						0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0
14					0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0
16				0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0
18			0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25
20		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25
24		0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.25	1.5	1.5
30	0.6	0.6	0.6	0.6	0.6	0.6	0.8	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5
35	0.6	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5	2.0	2.0
40	0.6	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
50	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0
60	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.25	1.25	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5
70	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0
80	0.6	0.8	0.8	0.8	0.8	1.0	1.25	1.25	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0
100	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0
120	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	4.0	4.0	4.0	4.0

Semi and Indirect Lighting-CEILING 24 FEET ABOVE WORK PLANE

Direct Lighting-SOURCES 20 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	1 0	200
8																			
10										0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8
12									0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8
14									0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0
16								0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0
18							0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0
20						0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0
24					0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25
30				0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.25	1.25	1.25	1.5
35		0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5
40	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5	1.5
50	0.6	0.6	0.6	0.6	0.6	0.6	0.8	1.0	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0
60	0.6	0.6	0.6	0.6	0.6	0.6	0.8	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
70	0.6	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5
80	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.25	1.25	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5
100	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.25	1.5	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
120	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.25	1.25	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0

Semi and Indirect Lighting-CEILING 30 FEET ABOVE WORK PLANE

TABLE 28.—*Continued*

Room Index

For Finding Coefficient of Utilization from Table 27

Direct Lighting-SOURCES 30 FEET ABOVE WORK PLANE

ROOM WIDTH	ROOM LENGTH—FEET																		
	10	12	14	16	18	20	24	30	35	40	50	60	70	80	100	120	140	170	200
8																			
10																			
12																			
14																			
16											0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8
18											0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8
20											0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8
24										0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8
30								0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
35								0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0
40							0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.25
50				0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.25
60				0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.0	1.0	1.25	1.25	1.25	1.5	1.5
70				0.6	0.6	0.6	0.6	0.6	0.6	0.8	1.0	1.0	1.25	1.25	1.25	1.5	1.5	1.5	1.5
80				0.6	0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.0	1.25	1.25	1.5	1.5	1.5	1.5	2.0
100				0.6	0.6	0.6	0.6	0.6	0.8	1.0	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0
120				0.6	0.6	0.6	0.6	0.8	0.8	1.0	1.25	1.25	1.5	1.5	1.5	2.0	2.0	2.0	2.5

Semi and Indirect Lighting-CEILING 45 FEET ABOVE WORK PLANE

TABLE 29

Computed Illumination Values

Using Depreciation Factor of 1.3

Area in Square Ft. per Lamp	Size of Lamp		COEFFICIENT OF UTILIZATION															
	Watts	Lumens	.14	.16	.18	.20	.22	.25	.28	.32	.36	.40	.45	.50	.55	.60	.65	.70
			FOOT-CANDLES															
60	100	1300	2.3	2.7	3.0	3.3	3.7	4.2	4.7	5.3	6.0	6.7	7.5	8.3	9.2	10.0	10.8	11.7
	150	2100	3.8	4.3	4.8	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	18.8
	200	3100	5.6	6.4	7.2	7.9	8.7	9.9	11.1	12.7	14.3	15.9	17.9	19.9	21.8	23.8	25.8	27.8
	300	4900	8.8	10.0	11.3	12.6	13.8	15.7	17.6	20.1	22.6	25.1	28.3	31.4	34.6	37.7	40.8	44.0
70	100	1300	2.0	2.3	2.6	2.9	3.1	3.6	4.0	4.6	5.1	5.7	6.4	7.1	7.9	8.6	9.3	10.0
	150	2100	3.2	3.7	4.2	4.6	5.1	5.8	6.5	7.4	8.3	9.2	10.4	11.5	12.7	13.8	15.0	16.2
	200	3100	4.8	5.4	6.1	6.8	7.5	8.5	9.5	10.9	12.3	13.6	15.3	17.0	18.7	20.4	22.1	23.8
	300	4900	7.5	8.6	9.7	10.8	11.8	13.5	15.1	17.2	19.4	21.5	24.2	26.9	29.6	32.3	35.0	37.7
80	100	1300	1.8	2.0	2.2	2.5	2.8	3.1	3.5	4.0	4.5	5.0	5.6	6.2	6.9	7.5	8.1	8.7
	150	2100	2.8	3.2	3.6	4.0	4.4	5.0	5.7	6.5	7.3	8.1	9.1	10.1	11.1	12.1	13.1	14.1
	200	3100	4.2	4.8	5.4	6.0	6.6	7.4	8.3	9.5	10.7	11.9	13.4	14.9	16.4	17.9	19.4	20.9
	300	4900	6.6	7.5	8.5	9.4	10.4	11.9	13.2	15.1	17.0	18.8	21.2	23.6	25.9	28.3	30.6	33.0
90	100	1300	1.6	1.8	2.0	2.2	2.4	2.8	3.1	3.6	4.0	4.5	5.0	5.6	6.1	6.7	7.2	7.8
	150	2100	2.5	2.9	3.2	3.6	3.9	4.5	5.0	5.7	6.5	7.2	8.1	9.0	9.9	10.8	11.7	12.6
	200	3100	3.7	4.2	4.8	5.3	5.8	6.6	7.4	8.5	9.5	10.6	11.9	13.2	14.5	15.9	17.2	18.5
	300	4900	5.9	6.7	7.5	8.4	9.2	10.5	11.7	13.4	15.1	16.8	18.8	20.9	23.0	25.1	27.2	29.2
100	100	1300	1.4	1.6	1.8	2.0	2.2	2.5	2.8	3.2	3.6	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	150	2100	2.3	2.6	2.9	3.2	3.6	4.0	4.5	5.2	5.8	6.5	7.3	8.1	8.9	9.7	10.5	11.3
	200	3100	3.3	3.8	4.3	4.8	5.2	5.9	6.7	7.6	8.6	9.5	10.7	11.9	13.1	14.3	15.5	16.7
	300	4900	5.3	6.0	6.8	7.5	8.3	9.4	10.6	12.1	13.6	15.1	17.0	18.8	20.7	22.6	24.5	26.4
110	100	1300	1.3	1.5	1.6	1.8	2.0	2.3	2.5	2.7	3.3	3.6	4.1	4.5	5.0	5.5	5.9	6.4
	150	2100	2.1	2.4	2.6	2.9	3.2	3.7	4.1	4.7	5.3	5.9	6.6	7.3	8.1	8.8	9.5	10.2
	200	3100	3.0	3.5	3.9	4.3	4.8	5.4	6.1	6.9	7.8	8.7	9.8	10.8	11.9	13.0	14.0	15.2
	300	4900	4.3	5.5	6.2	6.9	7.5	8.6	9.6	11.0	12.3	13.7	15.4	17.1	18.8	20.6	22.3	24.0
120	100	1300	1.2	1.3	1.5	1.7	1.8	2.1	2.3	2.7	3.0	3.3	3.8	4.2	4.6	5.0	5.4	5.8
	150	2100	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	9.4
	200	3100	2.8	3.2	3.6	4.0	4.4	5.0	5.6	6.3	7.1	7.9	8.9	9.9	11.0	12.0	13.0	14.0
	300	4900	4.4	5.0	5.7	6.3	6.9	7.9	8.8	10.1	11.3	12.6	14.1	15.7	17.3	18.8	20.4	22.0
130	100	1300	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
	150	2100	1.7	2.0	2.2	2.5	2.7	3.1	3.5	4.0	4.5	5.0	5.6	6.2	6.8	7.5	8.1	8.7
	200	3100	2.6	2.9	3.3	3.7	4.0	4.5	5.1	5.9	6.6	7.4	8.3	9.2	10.1	11.0	11.9	12.8
	300	4900	4.1	4.6	5.2	5.8	6.4	7.2	8.1	9.3	10.4	11.6	13.1	14.5	16.0	17.4	18.9	20.3
140	100	1300	1.0	1.1	1.3	1.4	1.6	1.8	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.3	4.6	5.0
	150	2100	1.6	1.8	2.1	2.3	2.5	2.9	3.2	3.7	4.2	4.6	5.2	5.8	6.3	6.9	7.5	8.1
	200	3100	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.1	6.8	7.7	8.5	9.4	10.2	11.1	11.9
	300	4900	3.8	4.3	4.9	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	18.8
160	150	2100	1.4	1.6	1.8	2.0	2.2	2.5	2.8	3.2	3.6	4.0	4.5	5.0	5.6	6.1	6.6	7.1
	200	3100	2.1	2.4	2.7	3.0	3.3	3.7	4.2	4.8	5.4	5.9	6.7	7.4	8.2	8.9	9.7	10.5
	300	4900	3.3	3.8	4.2	4.7	5.2	5.9	6.6	7.5	8.5	9.4	10.6	11.8	13.0	14.1	15.3	16.5
	500	8800	5.9	6.8	7.6	8.5	9.3	10.6	11.8	13.5	15.2	16.9	19.0	21.2	23.3	25.4	27.5	29.3
180	150	2100	1.3	1.4	1.6	1.8	2.0	2.2	2.5	2.9	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.3
	200	3100	1.8	2.1	2.4	2.6	2.9	3.3	3.7	4.2	4.8	5.3	5.9	6.6	7.3	7.9	8.6	9.3
	300	4900	2.9	3.4	3.8	4.2	4.6	5.2	5.9	6.7	7.5	8.4	9.4	10.5	11.5	12.6	13.6	14.7
	500	8800	5.3	6.0	6.8	7.5	8.3	9.4	10.5	12.0	13.5	15.0	16.9	18.8	20.7	22.6	24.4	26.3
200	150	2100	1.1	1.3	1.5	1.6	1.8	2.0	2.3	2.6	2.9	3.2	3.6	4.0	4.4	4.8	5.3	5.7
	200	3100	1.7	1.9	2.1	2.4	2.6	3.0	3.3	3.8	4.3	4.8	5.3	6.0	6.5	7.1	7.7	8.3
	300	4900	2.6	3.0	3.4	3.8	4.1	4.7	5.3	6.0	6.8	7.5	8.5	9.4	10.4	11.3	12.3	13.2
	500	8800	4.7	5.4	6.1	6.8	7.4	8.5	9.5	10.8	12.2	13.5	15.2	16.9	18.6	20.3	22.0	23.7
220	150	2100	1.0	1.2	1.3	1.5	1.6	1.8	2.1	2.4	2.6	2.9	3.3	3.7	4.0	4.4	4.8	5.1
	200	3100	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.5	3.9	4.3	4.9	5.4	5.9	6.5	7.0	7.5
	300	4900	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.2	6.9	7.7	8.6	9.4	10.3	11.1	12.0
	500	8800	4.3	4.9	5.5	6.2	6.8	7.7	8.6	9.8	11.1	12.3	13.8	15.4	16.9	18.5	20.0	21.5
250	200	3100	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.2	5.7	6.2	6.7
	300	4900	2.1	2.4	2.7	3.0	3.3	3.8	4.2	4.8	5.4	6.0	6.8	7.5	8.3	9.0	9.8	10.6
	500	8800	3.8	4.3	4.9	5.4	6.0	6.8	7.6	8.7	9.7	10.8	12.2	13.5	14.9	16.2	17.6	18.9
	750	14000	6.0	6.9	7.8	8.6	9.5	10.8	12.1	13.8	15.5	17.2	19.4	21.5	23.7	25.8	28.0	30.2
280	200	3100	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.4	3.8	4.3	4.7	5.1	5.5	6.0
	300	4900	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	9.4
	500	8000	3.4	3.9	4.4	4.8	5.3	6.0	6.8	7.7	8.7	9.7	10.9	12.1	13.3	14.5	15.7	16.9
	750	14000	5.4	6.2	6.9	7.7	8.5	9.6	10.8	12.3	13.8	15.4	17.3	19.2	21.2	23.1	25.0	26.9

TABLE 29.—*Continued*

Computed Illumination Values

Using Depreciation Factor of 1.3

Area in Square Ft. per Lamp	Size of Lamp		COEFFICIENT OF UTILIZATION															
	Watts	Lumens	.14	.16	.18	.20	.22	.25	.28	.32	.36	.40	.45	.50	.55	.60	.65	.70
			FOOT-CANDLES															
320	200	3100	1.0	1.2	1.3	1.5	1.6	1.9	2.1	2.4	2.7	3.0	3.4	3.7	4.1	4.5	4.9	5.2
	300	4900	1.6	1.9	2.1	2.4	2.6	2.9	3.3	3.8	4.2	4.7	5.3	5.9	6.5	7.1	7.7	8.2
	500	8800	3.0	3.4	3.8	4.2	4.7	5.3	5.9	6.8	7.6	8.5	9.5	10.6	11.6	12.7	13.8	14.8
	750	14000	4.7	5.4	6.1	6.7	7.4	8.4	9.4	10.8	12.1	13.5	15.1	16.8	18.5	20.2	21.9	23.6
360	200	3100	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.3	3.6	4.0	4.3	4.6
	300	4900	1.5	1.7	1.9	2.1	2.3	2.6	2.9	3.4	3.8	4.2	4.7	5.2	5.8	6.3	6.8	7.3
	500	8800	2.6	3.0	3.4	3.8	4.1	4.7	5.3	6.0	6.8	7.5	8.5	9.4	10.3	11.3	12.2	13.2
	750	14000	4.2	4.8	5.4	6.0	6.6	7.5	8.4	9.6	10.8	12.0	13.5	15.0	16.4	18.0	19.4	20.9
400	200	3100	0.8	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2
	300	4900	1.3	1.5	1.7	1.9	2.1	2.4	2.6	3.0	3.4	3.8	4.2	4.7	5.2	5.7	6.1	6.6
	500	8800	2.4	2.7	3.0	3.4	3.7	4.2	4.7	5.4	6.1	6.8	7.6	8.5	9.3	10 2	11.0	11.8
	750	14000	3.8	4.3	4.8	5.4	5.9	6.7	7.5	8.6	9.7	10.8	12.1	13.5	14.8	16.2	17.5	18.8
450	200	3100	0.7	0.8	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.6	2.9	3.2	3.5	3.7
	300	4900	1.2	1.3	1.5	1.7	1.8	2.1	2.3	2.7	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.9
	500	8800	2.1	2.4	2.7	3.0	3.3	3.8	4.2	4.8	5.4	6.0	6.8	7.5	8.3	9.0	9.8	10.5
	750	14000	3.4	3.8	4.3	4.8	5.3	6.0	6.7	7.7	8.6	9.6	10.8	12.0	13.2	14.4	15.6	16.8
500	300	4900	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3
	500	8800	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.9	5.4	6.1	6.8	7.4	8.1	8.8	9.5
	750	14000	3.0	3.4	3.9	4.3	4.7	5.4	6.0	6.9	7.8	8.6	9.7	10.9	11.9	12.9	14 0	15.1
	1000	20000	4.3	4.9	5.5	6.2	6.8	7.7	8.6	9.8	11.1	12.3	13.8	15.4	16.9	18.4	20.0	21.5
600	300	4900	0.9	1.0	1.1	1.3	1.4	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.5	3.8	4.1	4.4
	500	8800	1.6	1.8	2.0	2.3	2.5	2.8	3.2	3.6	4.1	4.5	5.1	5.6	6.2	6.8	7.3	7.9
	750	14000	2.5	2.9	3.2	3.6	4.0	4.5	5.0	5.7	6.5	7.2	8.1	9.0	9.9	10.8	11.7	12.6
	1000	20000	3.6	4.1	4.6	5.1	5.6	6.4	7.2	8.2	9.2	10.3	11.5	12.8	14.1	15.4	16.7	18.0
700	300	4900	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	2.0	3.2	3.5	3.8
	500	8800	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.5	3.9	4.4	4.8	5.3	5.8	6.3	6.8
	750	14000	2.2	2.5	2.8	3.1	3.4	3.8	4.3	4.9	5.5	6.2	6.9	7.7	8.5	9.2	10.0	10.8
	1000	20000	3.1	3.5	4.0	4.4	4.8	5.5	6.2	7.0	7.9	8.8	9.9	11.0	12.1	13.2	14.3	15.4
800	300	4900	0.7	0.8	0.8	0.9	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.6	2.8	3.1	3.3
	500	8800	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.2	4.7	5.1	5.5	5.9
	750	14000	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.3	4.8	5.4	6.1	6.7	7.4	8.1	8.8	9.4
	1000	20000	2.7	3.1	3.5	3.8	4.2	4.8	5.4	6.2	6.9	7.7	8.7	9.6	10.6	11.5	12.5	13.5
900	300	4900	0.6	0.7	0.8	0.8	0.9	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9
	500	8800	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3
	700	14000	1.7	1.9	2.2	2.4	2.6	3.0	3.4	3.8	4.3	4.8	5.4	6.0	6.6	7.2	7.8	8.4
	1000	20000	2.4	2.7	3.1	3.4	3.8	4.3	4.8	5.5	6.2	6.8	7.7	8.6	9.4	10.3	11.1	12.0
1000	300	4900	0.5	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.3	2.4	2.6
	500	8800	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.7	4.1	4.4	4.7
	700	14000	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.9	4.3	4.8	5.4	5.9	6.5	7.0	7.5
	1000	20000	2.2	2.5	2.8	3.1	3.4	3.8	4.3	4.9	5.5	6.2	6.9	7.7	8.5	9.2	10.0	10.8
1200	300	4900	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.6	1.7	1.9	2.0	2.2
	500	8800	0.8	0.9	1.0	1.1	1.2	1.4	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.4	3.7	3.9
	750	14000	1.3	1.4	1.6	1.8	2.0	2.2	2.5	2.9	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.3
	1000	20000	1.8	2.1	2.3	2.6	2.8	3.2	3.6	4.1	4.6	5.1	5.8	6.4	7.1	7.7	8.3	9.0
1400	300	4900	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.6	1.8	1.9
	500	8800	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.4	2.7	2.9	3.1	3.4
	750	14000	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
	1000	20000	1.5	1.8	2.0	2.2	2.4	2.7	3.1	3.5	4.0	4.4	4.9	5.5	6.0	6.6	7.1	7.7
1600	300	4900	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.3	1.4	1.5	1.6
	500	8800	0.6	0.7	0.8	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.1	2.3	2.5	2.8	3.0
	750	14000	0.9	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.4	3.7	4.0	4.4	4.7
	1000	20000	1.3	1.5	1.7	1.9	2.1	2.4	2.7	3.1	3.5	3.8	4.3	4.8	5.3	5.8	6.2	6.7
2000	300	4900	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3
	500	8800	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4
	750	14000	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.2	3.5	3.8
	1000	20000	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
2500	300	4900	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1
	500	8800	0.4	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.5	1.6	1.8	1.9
	750	14000	0.6	0.7	0.8	0.9	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.2	2.4	2.6	2.8	3.0
	1000	20000	0.9	1.0	1.1	1.2	1 4	1.5	1.7	2.0	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3

Modified Flux-of-light Method.—In order to facilitate the work of laying out an installation by eliminating as many calculations as possible, a system of curves, based upon the preceding discussion, has been drawn up to show the relation of the watts per square foot of floor area to the foot-candles of illumination, for different reflector equipments and grades of colors of walls and ceilings.

Accordingly, the following is a short and yet reasonably accurate method of designing a general lighting installation.

Before attempting to lay out a lighting installation, it is essential to ascertain a few facts concerning the building or room. These are:

Character of work to be carried on.
Floor dimensions.
Ceiling height (maximum hanging height).
Distance between columns (if any).
Color of walls and ceilings.

In order to facilitate the work, the first step should be to make a sketch, to scale, of the room under consideration.

Having the above information, before proceeding further, it is necessary to determine the type of reflector to be used. Having determined the proper reflector for the special class of building, proceed to case 1 for direct-lighting units, and to case 2 for semi-indirect and totally indirect units.

Case 1. *For Direct-lighting Units.*—When an even illumination over the entire working area is desired there is a fixed relation between hanging height and spacing for the several types of direct-lighting fixtures. It is always advisable to hang the units as high as possible, as this arrangement will provide more cross-light, and thus less dense shadows, and, again, by increasing the height, the spacing is increased and fewer outlets with the more efficient larger sizes of lamps may be used.

The ceiling height cannot be taken as the maximum hanging height, however, as some space is taken up by reflector and fittings. Where it is possible to hang the units close to the ceiling, a clearance of 1 ft. should be allowed. Again, if there is considerable overhead horizontal belting which would cast objectionable shadows from lamps hung above it, the maximum hanging height is the height of the lowest horizontal belting.

To determine hanging height and spacing of units for the case under consideration, proceed as follows:

From Fig. 110, showing the relation of the hanging height of a unit to its spacing, determine the maximum distance between units.

Divide the width of the room by the maximum spacing obtained above to determine the number of rows of outlets in the room. If this spacing does not divide into the width evenly, take the next larger whole number, which will be the number of rows of outlets.

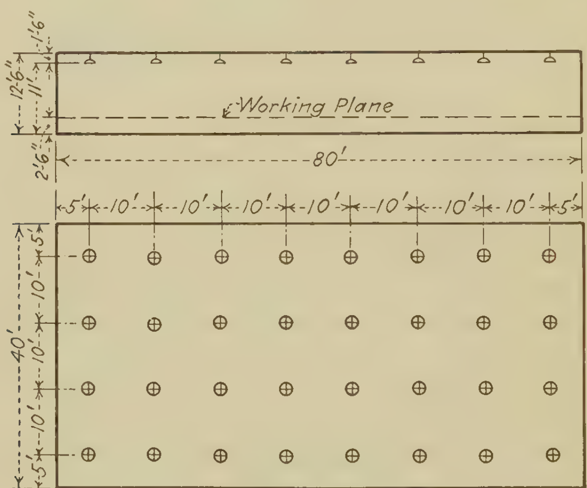


FIG. 108.—Location of outlets for the direct lighting system.

(In case the room is divided into bays by columns, as is usual in mill construction, consider each bay as a small separate room.)

Divide the number of rows of outlets into the width of the room, finding the new spacing, and thus determine the new hanging height from Fig. 110.

The distance between outlets in each row should be approximately the same as the distance between rows, and still make the length of the room evenly divided.

Divide the length of the room by the spacing between rows determined above, and if this does not come out as a whole number take the next larger whole number, which will be the number of outlets per row.

Now locate the outlets on the sketch, so that the distance from the wall to the first lamps will be one-half the distance between outlets (see Fig. 108). The spacing and the hanging height of the

units have now been determined. It remains to decide upon the size of the lamps to be used.

Multiply the distance between rows by the distance between outlets in rows to find the area to be covered by each lamp.

Refer to Table 24 for foot-candles required for the particular class of work to be carried on.

Find the equivalent watts per square foot from Figs. 113 to 116 for the particular type of reflector to be used, and multiply this

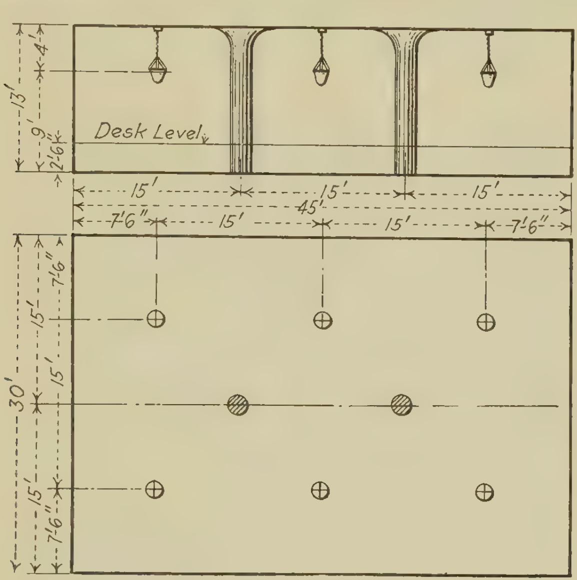


FIG. 109.—Plan of room and location of outlets for the indirect lighting system.

figure by the area per outlet. The result will be the watts necessary per outlet.

Select the nearest size of lamp, preferably the size larger. (It is well to note that the values given in Figs. 113 to 119 take into account a depreciation factor of 25 per cent for each system of lighting.)

Case 2. For Semi-indirect and Totally Indirect Units.—A method of procedure similar to case 1 may be followed for these types of fixtures, using the values given in Figs. 111 and 112 for spacing and hanging height.

Determine maximum spacing for a given ceiling height from Fig. 111 and determine suspension length of fixture for final spacing from Fig. 112.

The size of lamp to be used is found in a manner similar to case 1, using the values of watts per square foot for the desired foot-candles, found in Figs. 117, 118, and 119.

Example—Case 1

Character of work—armature winding.
Floor dimensions—40 ft. by 80 ft.
Ceiling height—12 ft. 6 in.
Columns—none.
Color of walls and ceilings—light.

Type of reflector equipment selected—RLM standard dome reflectors with bowl-enameled type-C lamps.

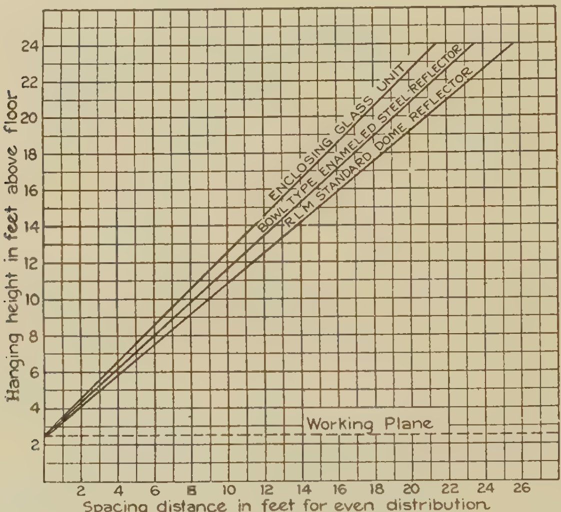


Fig. 110.—Relation of hanging height to spacing.

Maximum hanging height 11 ft. 6 in. From Fig. 110, spacing equals 10 ft. 9 in.

$\frac{40}{10.75} = 3.7$; therefore, there will be four rows of units.

$\frac{40}{4} = 10$ ft. . . . final spacing between rows. From Fig. 110, the final hanging height will be 11 ft. above the floor.

$\frac{80}{10} = 8$ . . . number of outlets in each row.

A layout of these outlets is shown in Fig. 108.

To determine size of lamp:

$$10 \text{ ft.} \times 10 \text{ ft.} = 100 \text{ sq. ft.—area for each lamp.}$$

Foot-candles desirable for this class of work, from Table 24, equals 10.

From Fig. 113 for more than one row of outlets and light surroundings, it will be found that 1.55 watts per square foot will produce 10 foot-candles with this equipment.

$$100 \times 1.55 = 155 \text{ watts per lamp.}$$

The lamp to be selected is therefore the 150-watt bowl-enameled type-C lamp.

Example—Case 2

Character of work—general office.
Floor dimensions—30 ft. by 45 ft.
Ceiling height—13 ft.
Columns—15-ft. centers.
Color of walls and ceiling—light.

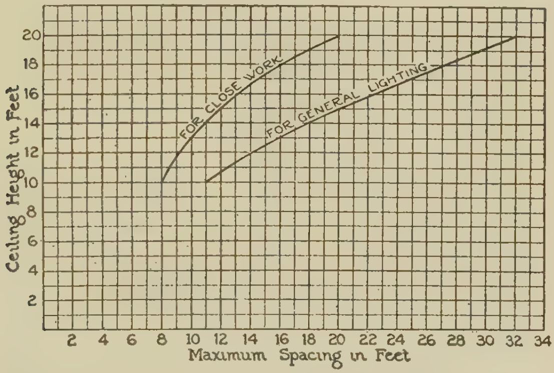


FIG. 111.—Relation of ceiling height to maximum spacing for semi-indirect and indirect luminaires.

Type of reflector equipment selected—deep-dish, dense-opal, semi-indirect luminaire.

Considering a bay as a room, the dimensions are 15 by 15 ft. From Fig. 111, the maximum spacing for a 13-ft. ceiling is 16 ft. and so one outlet per bay may be employed. From Fig. 112, the minimum suspension below the ceiling for the units should be 4 ft. The outlets thus determined are shown in Fig. 109.

To determine size of lamp:

$$15 \text{ ft.} \times 15 \text{ ft.} = 225 \text{ sq. ft.—area for each lamp.}$$

Foot-candles desirable for this class of work, from Table 24, equals 10.

From Fig. 119 for more than one row of outlets and light surroundings, it will be found that 2.2 watts per square feet will produce 10 foot-candles with this equipment.

$$225 \times 2.2 = 495 \text{ watts per lamp.}$$

The lamp to be selected is, therefore, the 500-watt, clear, type-C lamp.

Revising a Present Installation.—Many times it is advisable or necessary to use the present outlets in a building which is already

wired for lighting, but where the new high-intensity illumination has not been in use. In such cases, it is first necessary to determine the floor area of the building in square feet.

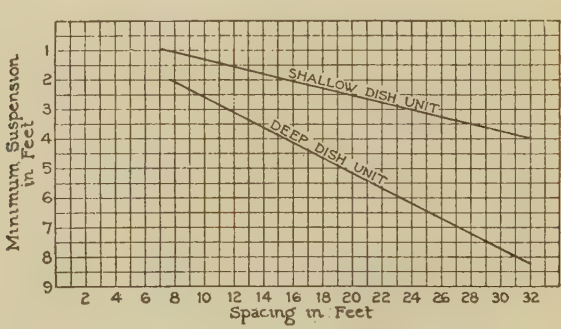


FIG. 112.—Minimum suspension below ceiling for various spacings of shallow dish and deep dish, semi-indirect and indirect units.

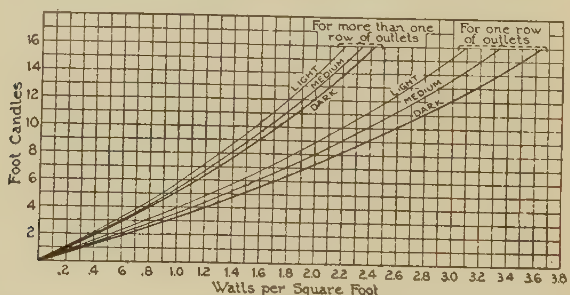


FIG. 113.—RML standard dome reflectors and bowl enameled Mazda C lamps.

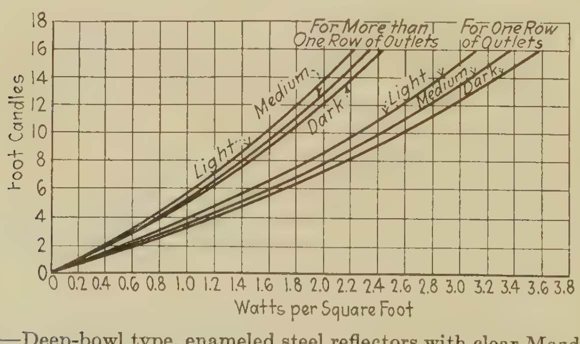


FIG. 114.—Deep-bowl type, enameled steel reflectors with clear Mazda C lamps.

Divide the area by the number of outlets to obtain the average area to be taken care of by each lamp.

Multiply this by the watts per square foot found in Figs. 113 to 119 for the particular work and surrounding conditions.

Select the nearest size of lamp, preferably the one larger, which it will be necessary to use.

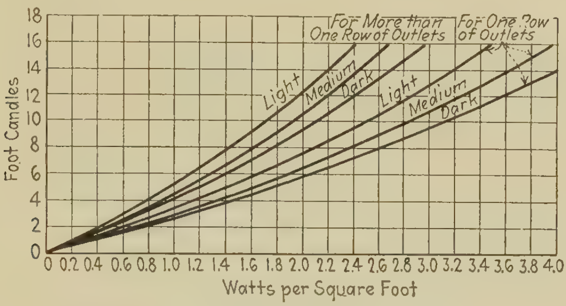


FIG. 115.—Deep-bowl type, dense opal glass reflectors with bowl enameled Mazda C lamps.

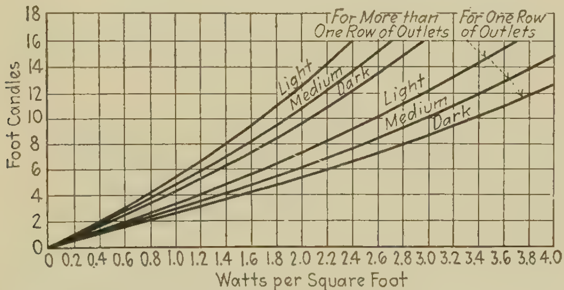


FIG. 116.—Enclosing opal glass units and clear Mazda C lamps.

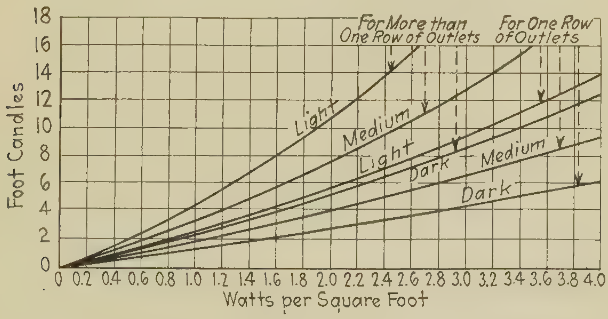


FIG. 117.—Light opal, semi-indirect units with clear Mazda C lamps.

To determine hanging height, knowing distance between outlets, use Figs. 110, 111, and 112. If this value is much greater

than the maximum permissible, due to a low ceiling, even illumination will not be obtained, and more outlets will be necessary. The room should be rewired and calculations made as outlined in cases 1 and 2.

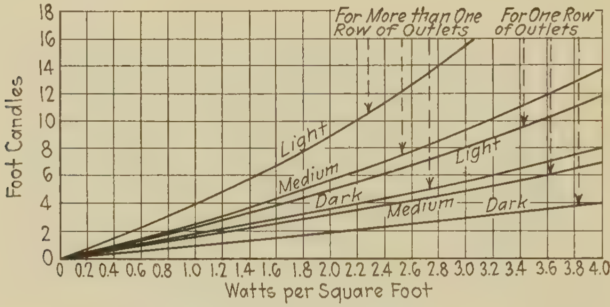


FIG. 118.—Dense opal semi-indirect units with clear Mazda C lamps.

The curves shown on the preceding pages are generally applicable to the more common commercial types of lighting units, such as those listed on following page.[1]

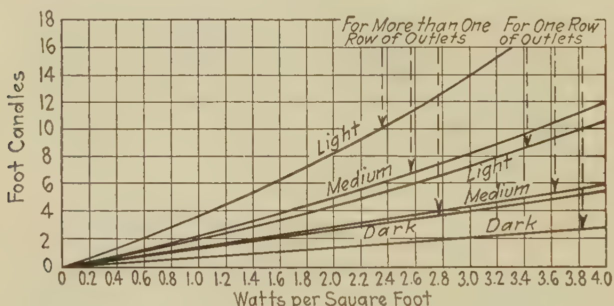


FIG. 119.—Indirect units with clear Mazda C lamps.

[1] It has seemed logical to keep the number of typical curves at a minimum, although it is recognized that different makes of any one group vary in efficiency. The values given are sufficiently accurate for practical purposes. For example, one might at first thought question the advisability of combining a diffusing enclosing globe, such as the Trojan, with a semienclosing metal and glass unit, such as the Brascolite. Detailed calculations reveal that, for extreme conditions the following values might be expected:

	Large room, light walls and ceiling	Large room, dark walls and ceiling
Trojan (1.7 watts per square foot)....	10 foot-candles	7.4 foot-candles
Brascolite (1.7 watts per square foot)..	10 foot-candles	8 foot-candles

TABLE 30

Trade name	Manufacturer	Figure number
Ace	Ivanhoe-Regent Works of General Electric Co.	116
Alexalite	Alexalite Co.	119
Amco	Art Metal Manufacturing Co.	114
Americolite	Americolite Co.	116
Apollo	Holophane Glass Co.	118
Archer	George Ainsworth Co.	116
Brascolite	Brascolite Co.	116
Cas-O-Lux	Cassidy Co., Inc.	116
Commercial Unit	Commercial Lighting Works	116
Daylight	Thomas Day Co.	116
Deluxlite	Harter Manufacturing Co.	116
Denzar	Beardslee Chandelier Manufacturing Co.	116
Duolier	C. G. Everson & Co.	116
Duplexalite	Duplex Lighting Works of General Electric Co.	118
Economy Light	H. S. Whiting Co., Inc.	118
Factrylite	Henkel & Best Co.	114
Four-in-One	L. Plaut & Co.	116
Franklin Unit	Gillinder & Sons	116
Holophane Reflector Refractor	Holophane Glass Co.	116
Industrolite	Brascolite Co.	114
Jefferson	Jefferson Glass Co.	116
Keldon	Ivanhoe-Regent Works of General Electric Co.	118
Maxolite Diffuser	Central Electric Co.	114
Mefco	H. G. McFadden Co.	116
Mellowlight	Wheeler Reflector Co.	116
Mohrlite	Mohrlite Co.	116
Monolier	C. G. Everson & Co.	116
Nitrolite	Harter Manufacturing Co.	114
Panamalite	Panama Electric Lamp Co.	116
Perfeclite	Perfeclite Co.	116
Phoenixlite	Phoenix Glass Co.	116
Ray-o-Day	Egan & Egan, Inc.	116
Reflectolyte	Reflectolyte Co.	116
Salite	Shapiro & Aronson, Inc.	116
Stranskylite	Stransky Manufacturing Co.	116
T-R-B	Mitchell Vance Co.	116
Trojan	Ivanhoe-Regent Works of General Electric Co.	116
X-Ray (direct)	National X-Ray Reflector Co.	114
X-Ray (indirect)	National X-Ray Reflector Co.	119

Light-density opalescent-glass semi-indirect bowls (Fig. 117) are available under the following trade names:

Alba	Luna	NuAcmelite
Cameo	Marble	Parian
Camia	Mefco	Selenite
Cora	Melilite	Silkene
Dandilite	Monax	Superba
Doric	Moonstone	Translux
Druid	Nitroglas	Una
Equalite	Nitrolite	Veluria
Frink	Nomalite	

Heavy-density opalescent-glass semi-indirect bowls (Fig. 118) are available under the following trade names:

Berylite	Ivre	Sudan
Calcite	Nebulite	

Wiring.—The standards for proper wiring from a protective basis are established by local underwriters' codes and ordinances. These must be adhered to. The choice between different systems is governed largely by economic considerations and need not be discussed here.

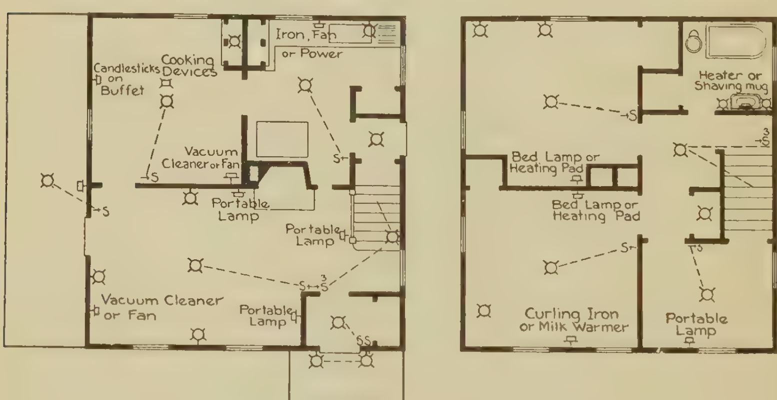


Fig. 120.—Location of outlets for a typical small house.

Attention should be directed to the desirability of making the initial installation complete. A given amount of installation work can be done at much less expense when doing the original work than at a later date. The mistake is often made of omitting convenience outlets and wall switches in order to keep down the cost of wiring. A satisfactory layout for the average home would be such as pictured in Fig. 120.

The Elexit or the standardized luminaire receptacle should be incorporated in each house wired in the future. This device makes it possible to change bracket or ceiling luminaires at will, without the delay and expense of calling in an electrician to make the connections (see Fig. 121).

A person living in a rented home can use his own distinctive, individual luminaires just as he does his pictures, draperies, and furniture. The special wiring devices which add materially to the convenience of the installation are many. Among them might be mentioned:

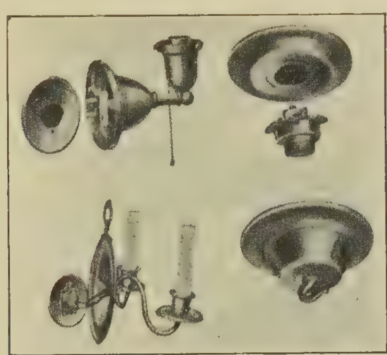


FIG. 121.—Detachable wall brackets and ceiling luminaires.

The switch handle or small indicator on a pull-chain socket provided with luminous material which glows in the dark, making it possible to locate the control readily.

Switches with small lamps concealed in their mechanism which serve to indicate that the attic or cellar lights are burning. Buzzing devices serve the same purpose.

Switches which can be attached to the ceiling or concealed in a canopy where wall switches are missing and it is not deemed advisable to do any extensive wiring.

Three-way switches for controlling the light from two points.

Two or more circuit switches in one mechanism to produce various degrees of lighting by pushing or turning the button a certain number of times.

Switches which operate automatically when a closet door is opened or closed.

Master switches for lighting the whole house from the owner's bedside in case of emergency.

Convenience receptacles which can be installed in the wall, baseboard, or floor or under a table. These should be of the standard type to take a plug with ¼-in. parallel blades spaced ½ in. apart so that all plugs are interchangeable.

Bell-ringing transformers which do away with maintaining batteries for this purpose.

On the following pages are given data on copper wire and a set of standard symbols for wiring plans as adopted and recommended by the National Electrical Contractors' Association of the United States and the American Institute of Architects.

TABLE 31

Table of Dimensions, Weights and Resistances of Pure Copper Wire

Brown Sharpe Gage

Gauge No.	Diam. Inches	AREA: Circular Mils(d^2) 1 Mil = .001 Inch	WEIGHT: Lbs. per Mile	WEIGHT: Lbs. per 1000 Feet	Length: Feet per Lb.	RESISTANCE AT 75° F.: Length Feet per Ohm	RESISTANCE AT 75° F.: R Ohms per 1000 Feet	RESISTANCE AT 75° F.: Ohms per Lb.	Carrying Capacities: Rub. Ins. Amperes	Carrying Capacities: Other Ins. Amperes	Gauge No.
*	1.152	1000000.	16165.	3050.	.3275	95100.	.01051	.000003442	650	1000	
*	1.035	800000.	12932.	2440.	.4100	76100.	.01313	.000005380	550	840	
*	.963	700000.	11315.5	2135.	.4680	66600.	.01501	.000007030	500	760	
*	.891	600000.	9699.	1830.	.5460	57100.	.01751	.000009579	450	680	
*	.819	500000.	8082.5	1525.	.6550	47500.	.02101	.00001376	400	600	
*	.728	400000.	6466.	1220.	.8200	38050.	.02627	.00002155	325	500	
*	.590	250000.	4038.6	762.	1.32	23750.	.04203	.00005600	240	350	
0000	.4600	211600.	3375.66	639.3	1.56	20383.	.04906	.00007673	225	325	0000
000	.4906	167805.	2677.01	507.0	1.97	16165	.06186	.00012039	175	275	000
00	.3648	133079.	2123.03	402.0	2.49	12820	.07801	.00019423	150	225	00
0	.3248	105538.	1683.58	318.8	3.14	10166	.09838	.00038500	125	200	0
1	.2893	83694.	1335.21	252.8	3.99	8062.3	.12404	.00048994	100	150	1
2	.2576	66373.	1058.85	200.5	4.99	6393.7	.15640	.00078045	90	125	2
3	.2294	52634.	839.68	159.0	6.29	5070.2	.19723	.0012406	80	100	3
4	.2043	41742.	665.91	126.1	7.93	4021.0	.24869	.0019721	70	90	4
5	.1819	33102.	528.05	100.0	10.00	3188.7	.31361	.0031361	55	80	5
6	.1620	26250.	418.81	79.32	12.61	2528.7	.39546	.0049868	50	70	6
7	.1442	20816.	332.11	62.90	15.90	2005.2	.49871	.0079294	38	54	7
8	.1284	16509.	263.37	49.88	20.05	1590.3	.62881	.012608	35	50	8
9	.1144	13094.	208.88	39.56	25.28	1261.3	.79281	.020042	28	38	9
10	.1018	10381.	165.63	31.37	31.38	1000.0	1.	.031380	25	30	10
11	.0907	8234.	131.37	24.88	40.20	793.18	1.2607	.050682	23	27	11
12	.0808	6529.	104.17	19.73	50.69	629.02	1.5898	.080585	20	25	12
13	.0719	5178.	82.63	15.65	63.91	498.83	2.0047	.12841	17	23	13
14	.0640	4106.	65.68	12.44	80.38	395.60	2.5278	.20322	15	20	14
15	.0570	3256.	51.96	9.84	101.63	321.02	3.1150	.31658	..	..	15
16	.0508	2582.	41.24	7.81	128.14	248.81	4.0191	.51501	6	10	16
17	.0452	2048.	32.68	6.19	161.59	197.30	5.0683	.81900	.	.	17
18	.0403	1624.	25.92	4.91	203.76	156.47	6.3911	1.3023	3	5	18

STANDARD SYMBOLS FOR ELECTRICAL EQUIPMENT OF BUILDINGS

Approved as an "Tentative American Standard," March 6, 1924.

Ceiling Outlet	
Ceiling Outlet (Gas and Electric)	
Ceiling Lamp Receptacle—Specification to Describe Type such as Key, Keyless or Pull Chain	R
Ceiling Outlet for Extensions	E
Ceiling Fan Outlet	
Floor Outlet	
Drop Cord	D
Wall Bracket	
Wall Bracket (Gas and Electric)	
Wall Outlet for Extensions	E
Wall Fan Outlet	
Wall Lamp Receptacle—Specification to Describe Type such as Key, Keyless or Pull Chain.	R
Single Convenience Outlet	
Double Convenience Outlet	2
Junction Box	J
Special Purpose Outlet—Lighting, Heating and Power as Described in Specification	
Special Purpose Outlet—Lighting, Heating and Power as Described in Specification	
Special Purpose Outlet—Lighting, Heating and Power as Described in Specification	
Exit Light	
Floor Elbow	O^E
Floor Tee	O^T
Pull Switch	P.S.
Local Switch—Single Pole	S^1
Local Switch—Double Pole	S^2
Local Switch—3 Way	S^3
Local Switch—4 Way	S^4
Automatic Door Switch	S^D
Key Push Button Switch	S^K
Electrolier Switch	S^E
Push Button Switch and Pilot	S^P

Remote Control Push Button Switch	S^R
Tank Switch	T.S.
Motor	
Motor Controller	M.C.
Lighting Panel	
Power Panel	
Heating Panel	
Pull Box	
Cable Supporting Box	
Meter	
Transformer	
Branch Circuit, Run Concealed under Floor Above	
Branch Circuit, Run Exposed	
Branch Circuit, Run Concealed Under Floor	
Feeder Run, Concealed under Floor Above	
Feeder Run, Exposed	
Feeder Run, Concealed under Floor	
Pole Line	
Push Button	
Buzzer	
Bell	
Annunciator	
Interior Telephone	
Public Telephone	
Local Fire Alarm Gong	F
City Fire Alarm Station	
Local Fire Alarm Station	F
Fire Alarm Central Station	FA
Speaking Tube	
Nurse's Signal Plug	N

Maid's Plug	M
Horn Outlet	
District Messenger Call	
Clock (Secondary)	
Clock (Master)	
Time Stamp	
Electric Door Opener	
Watchman Station	W
Watchman Central Station Detector	W
Public Telephone—P. B. X. Switchboard	P.B.X.
Interior Telephone Central Switchboard	I.X.
Interconnection Cabinet	
Telephone Cabinet	
Telegraph Cabinet	
Special Outlet for Signal System as Described in Specification	
Battery	
Signal Wires in Conduit Concealed Under Floor	
Signal Wires in Conduit Concealed under Floor Above	
This Character Marked on Tap Circuits Indicates 2 No. 14 Conductors in ½-in. Conduit (see note)	ǁ
3 No. 14 Conductors in ½-in. Conduit	ǀǀǀ
4 No. 14 Conductors in ¾-in. Conduit Unless Marked ½-in.	ǀǀǀǀ
5 No. 14 Conductors in ¾-in. Conduit	ǀǀǀǀǀ
6 No. 14 Conductors in 1-in. Conduit Unless Marked ¾-in.	ǀǀǀǀǀǀ
7 No. 14 Conductors in 1-in. Conduit	ǀǀǀǀǀǀǀ
8 No. 14 Conductors in 1-in. Conduit	ǀǀǀǀǀǀǀǀ

Note—If larger conductors than Number 14 are used, use the same symbols and mark the conductor and conduit size on the run.

SPONSORS: American Institute of Architects
American Institute of Electrical Engineers
Association of Electragists—International

CHAPTER X

INCANDESCENT, ARC, AND VAPOR LAMPS

Incandescent Lamps.—The first commercial incandescent lamp appears to have been produced by Edison in 1879. The filament consisted of carbonized paper. Later, filaments of carbonized bamboo were used and these were later improved by coating them with a hydrocarbon. In 1893 a process of making a cellulose filament from absorbent cotton dissolved in zinc chloride was discovered. The solution had the consistency of thick molasses and was forced through a die, in the form of fine thread, into an alcohol bath, which hardened it.

This filament was of uniform constitution and size and, after being carbonized, formed a filament of remarkable strength and flexibility. After mounting in the bulb, the filament was heated by passing an electric current through it while in the presence of a hydrocarbon vapor. This vapor was decomposed and carbon deposited upon the filament, forming a smooth, dense coating and correcting for any lack of uniformity that might exist. This lamp consumed about 3.1 watts per mean horizontal candle power.

The *Gem* or "*Metallized*" carbon-filament lamp was put on the market in 1905. The filament of this lamp was made by heating a treated carbon filament to the high temperature of the electric furnace. This treatment changed the temperature coefficient of resistivity from negative to positive—hence the expression "metallized" carbon filament. This lamp consumed about 2.5 watts per mean horizontal candle power.

The *Nernst lamp*, a German invention, came into commercial use in this country in 1900. It possessed a "glower," heater, "ballast," and cut-out (Fig. 122). The glower consisted mainly of zirconium oxide, and operated in the open air. It was a non-conductor when cold, so had to be heated before current would pass through it. This was accomplished by an electric heating coil, made of platinum wire, located just above the glower. As

the glower became heated and current passed through it, the heater was automatically disconnected by an electromagnet cut-out.

The glower had a decided negative temperature coefficient, so a steadying resistance or ballast was put in series with it. This consisted of an iron wire mounted in a glass bulb filled with hydrogen gas. Iron has a positive temperature coefficient of resistivity which is very marked at the temperature at which the ballast was operated.

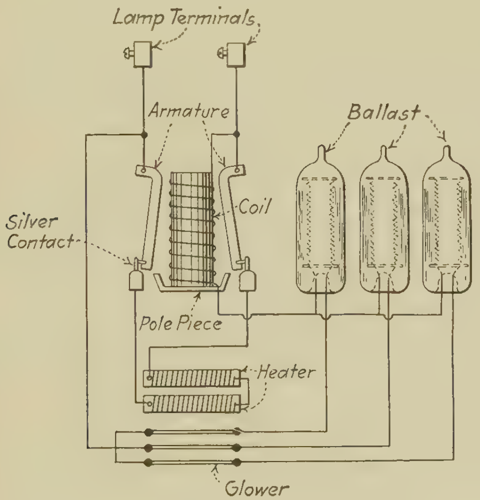


FIG. 122.—Three glower Nernst lamp.

The lamp operated on 220-volt alternating-current circuits. The glower consumed 0.4 amp. One, two, three, four, and six glower lamps were made, consuming 88, 196, 274, 392, and 528 watts respectively. The multiple glower lamps were more efficient, owing to the heat radiating from one glower to another. Their efficiencies were from 3½ to 5 lumens per watt and their average candle power throughout life was about 80 per cent of initial. The lamp disappeared from the market about 1912.

The *osmium lamp* was commercially introduced in Europe in 1905. It had a very fair maintenance of candle power during its life, and an average efficiency of about 5 lumens per watt. Osmium is a very rare and expensive metal, usually found associ-

ated with platinum, and therefore difficult to obtain. The lamp was extremely fragile.

The *tantalum lamp*, having a filament of tantalum, a ductile metal, had an initial efficiency of about 5 lumens per watt. When used on alternating-current circuits the filament crystalized and a shorter life resulted than on direct-current circuits. It was on the market from 1906 to 1913.

The *tungsten-filament lamp* became commercially available in this country in 1907. The filaments were made by mixing finely divided tungsten powder with a binder to form a paste, and then squirting the paste through a die, producing a thread. Hairpin loops of this thread were treated to remove the binder and several of them were mounted in series within the bulb to give the necessary resistance. The lamp was fragile, but could be operated at 7 lumens per watt.

A process of making tungsten ductile was discovered by Dr. Coolidge about 1911. This made possible a continuous uniform filament of drawn ductile tungsten, simplified the manufacture of the lamp, and very materially increased its ruggedness.

Research by Dr. Langmuir made it possible greatly to increase the efficiency of the tungsten lamp by the use of an inert gas in the bulb. Lamps of this type were produced commercially in 1913. These are known as the type-C lamps, to distinguish them from the vacuum or type-B lamps.

The current passing through a filament and the temperature at which it is to operate are dependent upon the diameter of the filament. A tungsten filament of large diameter can be operated at a higher temperature than one of smaller diameter, as a greater amount of filament material can evaporate without reducing its diameter to as great an extent, and, as previously stated, a filament can be operated under gas pressure at a higher temperature than in a vacuum.

A lamp, to consume a given wattage at a given voltage, must, of course, have a filament of definite resistance. The resistance of tungsten depends upon its temperature—the higher the temperature the greater its resistance (Fig. 123). Anchors and leading-in wires conduct heat away, cooling and therefore reducing the resistance of the filament at these points. If gas is used in the lamp, it also takes heat from the filament, tending to reduce its resistance, which is compensated for by increasing the current density, that is, by using a smaller-diameter filament.

There are many factors, therefore, which determine the diameter and the length of the filament in each lamp. The approximate filament dimensions of a few lamps are given in Table 32.

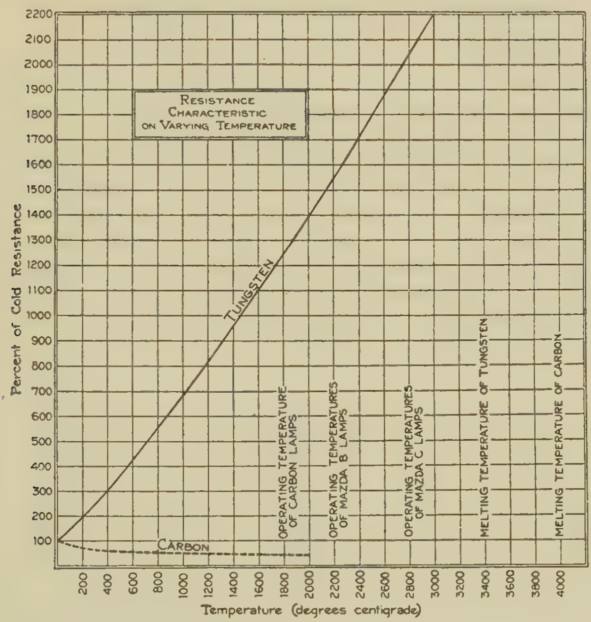


FIG. 123.—Resistance characteristic of tungsten and carbon filaments with varying temperature expressed in degrees Centigrade.

TABLE 32

Lamp	Length of filament, inches	Diameter of filament, thousandths of an inch
Carbon—50 watts, 110 volts	9	4.00
Type B—25 watts, 110 volts	18¼	1.16
Type B—50 watts, 110 volts	22	1.82
Type B—50 watts, 220 volts	37	1.18
Type C—500 watts, 110 volts	34¾	7.92
Type C—30 volts, 30 amp.[1]	11½	24.50

[1] Motion-picture lamp.

In manufacturing a tungsten lamp the filament is supported on a "mount," as shown in Fig. 124, which is inserted in the bulb. The flange on the glass tube of the mount is welded to the neck of the bulb, the air is exhausted, and the bulb is sealed. The base is then put on and the leading-in wires soldered to it, completing the manufacture of a type-B lamp. In the type-C lamp, after the air has been exhausted the bulb is filled with gas and sealed.

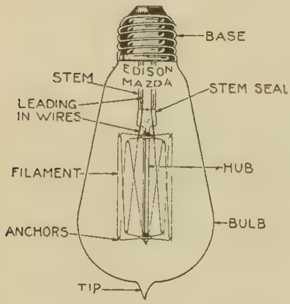


Fig. 124.—Names of principal parts of a tungsten lamp.

The characteristic curves of tungsten lamps are shown in Fig. 125. It will be seen that a lamp operating 10 per cent below normal voltage will give only about 70 per cent normal candle power.

The performance curves through life are given in Figs. 126 and 127. The gas-filled lamp maintains its candle power much

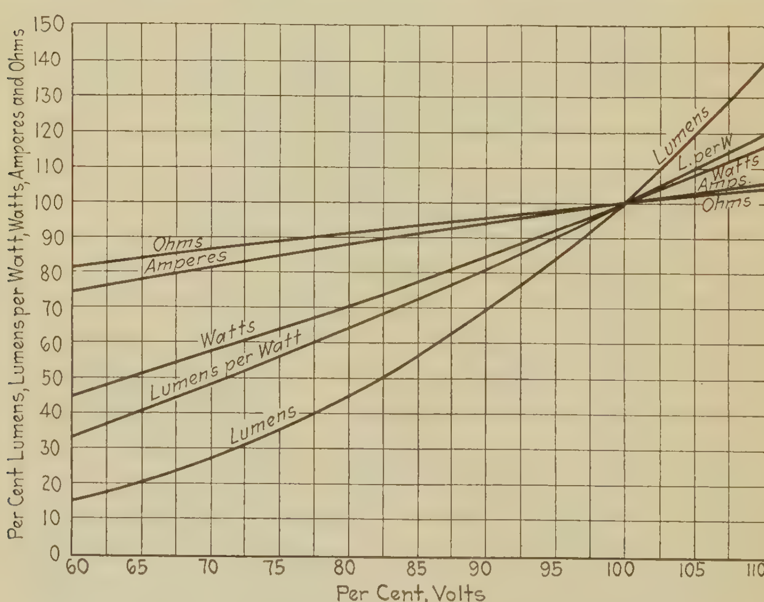


Fig. 125.—Characteristic curves of tungsten lamps.

better than the vacuum lamp. The average life of tungsten lamps as generally rated is about 1,000 hr. Some may fail after

a few hours' operation, while others may far surpass this figure. Typical results of this nature are shown in Fig. 128.

One feature not always appreciated is that lamps are designed to burn at their *rated* voltage. If the supply voltage, for instance,

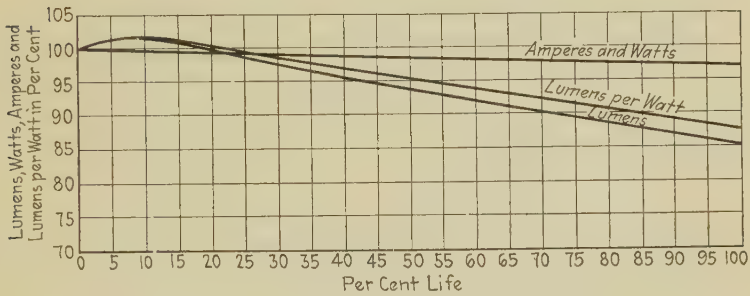


FIG. 126.—Typical performance curves of type B lamps.

is 115, lamps should be obtained with this rating to secure 100 per cent efficiency and life. A 110-volt lamp on this circuit would have only 50 per cent of its normal life. The other mistake, using an overvoltage lamp, for example, one rated 125 volts, would result in securing only 75 per cent light.

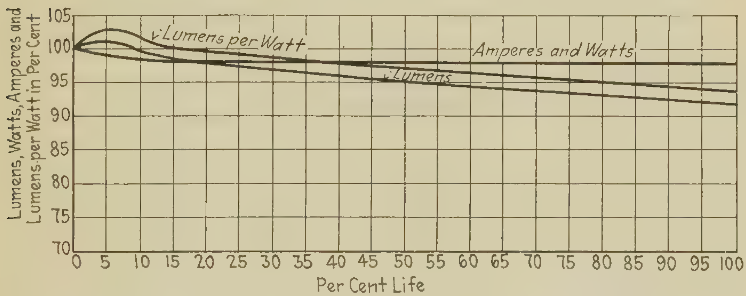


FIG. 127.—Typical performance curves of type C lamps.

There are about 200 types and sizes of tungsten-filament lamps now standard for various lighting services. For 110-volt service, lamps are made in sizes from 10 to 1,000 watts (see Table 23). In the smaller sizes, some are made in round- and tubular-shaped bulbs for ornamental lighting, in addition to the candelabra lamps used in ornamental luminaires.

For 220-volt service, lamps range in size from 25 to 1,000 watts. For sign lighting, 5-watt, low-voltage lamps are made, and for 30-volt service, such as train lighting and gas-engine-driven dynamo sets for a rural home service, there are 5- to 100-watt lamps. Concentrated-filament lamps are made for stereopticon and moving-picture service, flood lighting, etc. in sizes from 100 to 1,000 watts, for street-railway headlights in sizes below 100 watts, and for locomotive headlights in sizes from 100 to 250 watts. Lamps are made for series street-lighting circuits in sizes from 60 to 2,500 c.p. Miniature lamps include those for

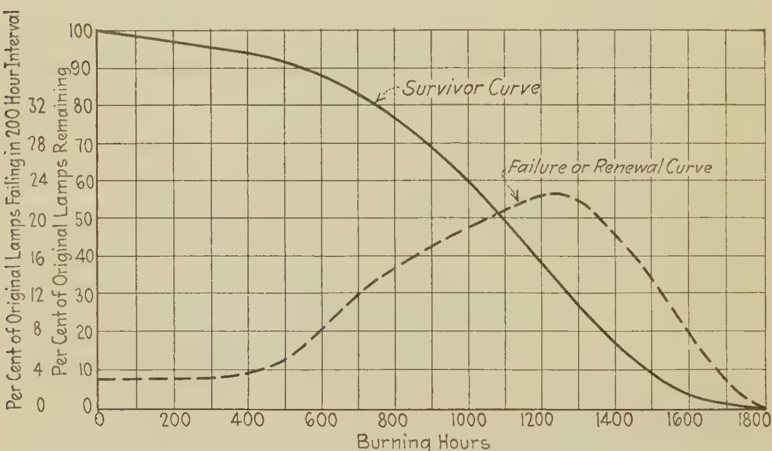


FIG. 128.—Typical survivor curve and corresponding curve of renewals for tungsten lamps.

flashlights, automobiles, Christmas trees, surgical and dental service, etc. They range from ½ to 21 c.p., and from 2½ to 24 volts, depending on the service. (The constructions of some of these lamps are shown in Fig. 129.)

The tungsten lamp is widely known as the "Mazda" lamp, a trade name copyrighted by one of the large manufacturing companies. The Mazda type-C lamp is available in a number of different styles. The "white" lamp has a white diffusing bulb. The "daylight" lamp has a special blue-glass bulb, which absorbs some of the yellow rays and gives an approximate daylight color. An excellent enamel for spraying the bowls of lamps has been developed. It is white, has good diffusing qualities, and will not chip, crack, discolor, nor depreciate. The relative

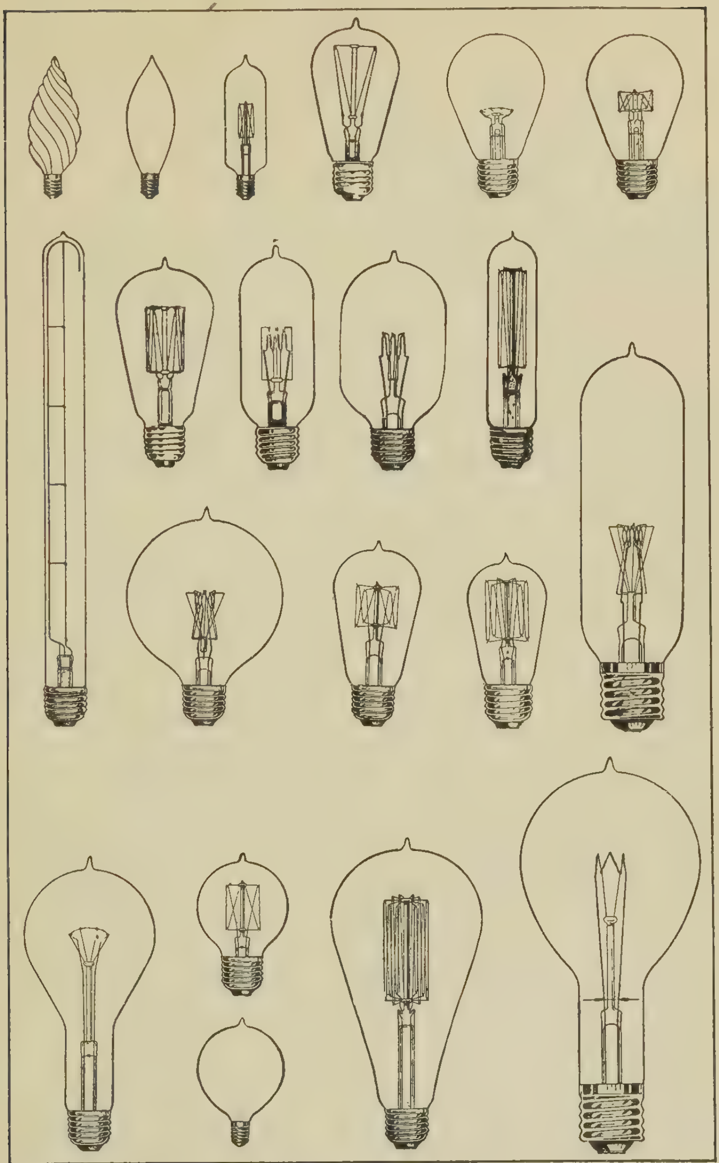


Fig. 129.—Some of the tungsten filament lamps.

efficiencies of the diffusing bulbs are given in the following table:

Table 33

	Total lumens, per cent
Clear lamp	100
Bowl frosted	97.5
Bowl enameled	92
All frosted	92
White lamp	88

It should be remembered that the diffusing qualities of the white bulb and the enamel finish are much higher than the frosted or etched surface.

Data concerning the rating, candle power, and efficiency of tungsten lamps will be found in Table 23.

Arc Lamps.—The first arc lamps used for street lighting had long electrodes of carbon and were of the open-arc type. These date, commercially, from about 1878. The electrodes were rapidly consumed, lasting from 8 to 16 hr., depending on their size and length. About 1893 it was found that, by placing a tight-fitting globe about the arc, the life of the carbons was increased ten to twelve times due to the restricted amount of oxygen admitted to the hot carbon tips. This lamp replaced the open arc and was used extensively on the series systems of lighting.

The *flame arc lamp* was produced by Bremer in Germany in 1898. The electrodes consisted of carbons impregnated with calcium fluoride. These lamps were high candle-power units, giving a brilliant yellow light which came from the arc flame. Two flame arc lamps were operated in series on 110-volt circuits. They consumed 550 watts each, giving an efficiency of about 35 lumens per watt on direct current and about 30 lumens per watt on alternating current.

The use of barium salts in the carbon gave a white light with an efficiency of 18 and 15 lumens per watt on direct and alternating currents respectively. By using strontium salts in the carbons, a red light was obtained at a considerably lower efficiency.

Flaming arc lamps were remarkably efficient, but their maintenance expense was high. Later, about 1908, enclosed-flame arc lamps were made which increased the life of the electrodes.

The flame arc lamp has been replaced by the gas-filled tungsten lamp.

The *luminous* or *magnetite arc lamp* owes its origin to the chemical research of Dr. Steinmetz in an endeavor to produce an arc lamp more efficient than the preexisting types and at the same time having a life for its electrodes comparable with those of the enclosed-arc lamp. The material of the cathode, as finally adopted, consisted of magnetite and titanium oxide. The magnetite particles make the arc stream a good conductor, but they are not very luminous; consequently the titanium oxide is introduced to furnish luminescence.

It was found that the magnetite was consumed faster than was necessary to produce the same efficiency and a small amount of chromium was introduced, which has a higher melting point than magnetite, although similar chemically. This restrained the molten magnetite and retarded the consumption of the electrode.

The luminous intensity of the lamp is due to the incandescent particles of titanium supplied by the cathode and carried into the arc stream by the electric current. As a result of this phenomenon, the negative electrode is the only one consumed, if the anode, which is of copper, is of sufficient size to conduct the excessive heat and not reach the evaporization temperature. If the anode is of too great size, the material from the cathode will condense upon it; therefore, the approximate dimensions of the positive electrode must be determined from these two considerations. The spectrum of the arc shows the characteristics of the material of the cathode and is not affected by the constituents of the anode. With the magnetite-titanium cathode, the light emitted is of intense brilliancy and whiteness.

The arc burns in the open air at about 75 volts. The magnetite electrode has a life of about 350 hr. The 4-amp. lamp has an efficiency of 11½ lumens per watt. A high-efficiency 4-amp. electrode, having a shorter life, gives 17 lumens per watt. A 6.6-amp. lamp is also made, giving an efficiency of about 18 lumens per watt with regular electrodes.

The peculiarities of the arc are such that Halvorson invented a new principle of control. The electrodes are normally apart (see Fig. 130). In starting, they are drawn together by a starting magnet with sufficient force to dislodge the slag which forms on the negative electrode and which becomes an insulator when cold.

Current then passes through the electrodes and through a series magnet, which opens the circuit through the starting magnet. This allows the lower electrode to fall a fixed distance—about seven-eighths of an inch—drawing the arc. As the negative electrode is consumed, the length and the voltage of the arc increase. When the magnet in shunt with the arc becomes sufficiently energized, it closes the contacts in the circuit of the starting magnet, causing the electrode to pick up and start off again.

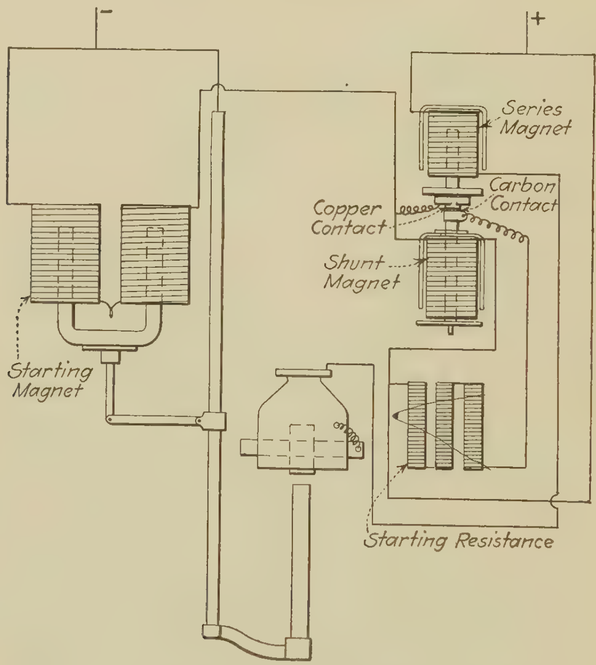


FIG. 130.—Diagram of series magnetite arc lamp.

The luminous arc lamps requiring direct current for their operation are generally supplied by constant-current transformers through mercury-arc rectifiers, as shown in Fig. 131.

This lamp and its characteristics will be discussed in greater detail under the subject of Street Lighting.

Vapor Lamps.—The mercury-vapor lamp is the result of experimentation by Peter Cooper Hewitt. He finally produced an arc in vacuum in a 1-in. glass tube 45 in. long for 110-volt direct-current circuits in 1901. The tubes hung about 15 deg.

from the horizontal. The lower end contained a small quantity of mercury. The terminals were at each end of the tube and the arc was first started by tilting the tube by hand, so that a thin stream of mercury bridged the two terminals. The current immediately vaporized the mercury, starting the arc. A resist-

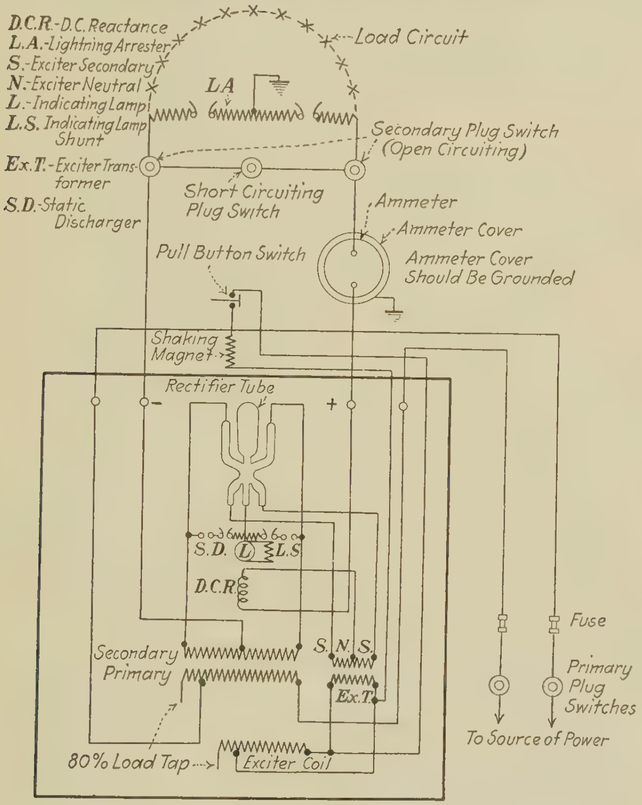


FIG. 131.—Connections of combined unit mercury arc rectifier outfit with remote controlled non-automatic shaking device.

ance was put in series with the arc to maintain a constant current on constant-potential circuits.

Automatic starting devices were later developed, one of which consisted of an electromagnet that tilted the lamp, and the other of an induction coil giving a high voltage which, in discharging, started the arc.

The lamp consumed 3½ amp. at 110 volts and gave 12½ lumens per watt with direct current.

The mercury arc is peculiar in that it will allow current to pass through it in only one direction.

The alternating-current lamp made use of the principle of the mercury rectifier in addition to that of the direct-current mercury lamp in order to keep the current through the tube unidirectional. This was accomplished by connecting the negative electrode to the middle point of a transformer winding and having two positive electrodes located at the same end of the tube and connected to the two ends of the winding, as shown in Fig. 132.

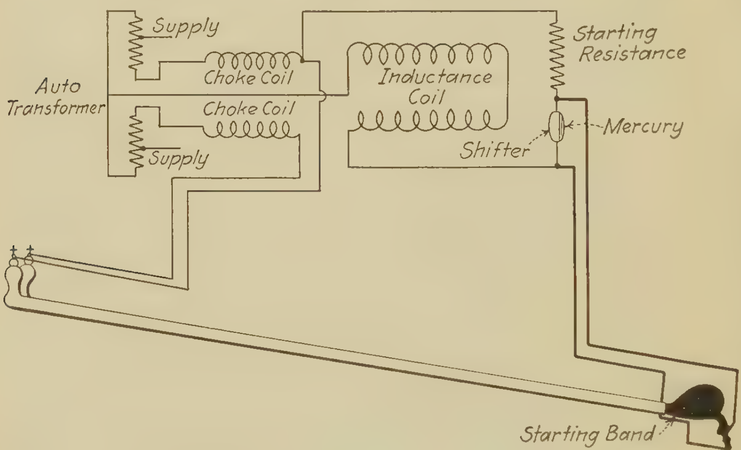


Fig. 132.—Diagram of Cooper-Hewitt lamp for use on alternating current.

During one-half cycle current passes from one end of the transformer winding through one positive electrode to the negative, while during the other alternation current passes through the other positive electrode. The inductance is in series with the negative electrode, producing a steadying effect on the current and preventing it from falling to zero at the end of each half cycle. The alternating-current lamp also required a ballast for best operation. The power factor of the lamp was from 80 to 85 per cent. Its efficiency is a little less than that of the direct-current lamp.

The *quartz mercury-vapor lamp* has a tube of quartz instead of glass, making it possible to operate at a much higher temperature and thereby obtains a much greater efficiency. The lamp is still deficient in red rays and gives out a considerable amount of ultra-violet radiation. These ultra-violet rays will kill bacteria,

and the lamp is being used to a certain extent for such purposes as the purification of water. It is also used for testing the stability of dyes. These rays are very harmful to the eyes. They are absorbed by ordinary glass, however, so when this lamp is used as an illuminant an enclosing globe must be used.

This lamp appeared in Europe in 1912, but has not been used to any extent in this country as an illuminant. The lamp has an efficiency of 26 lumens per watt.

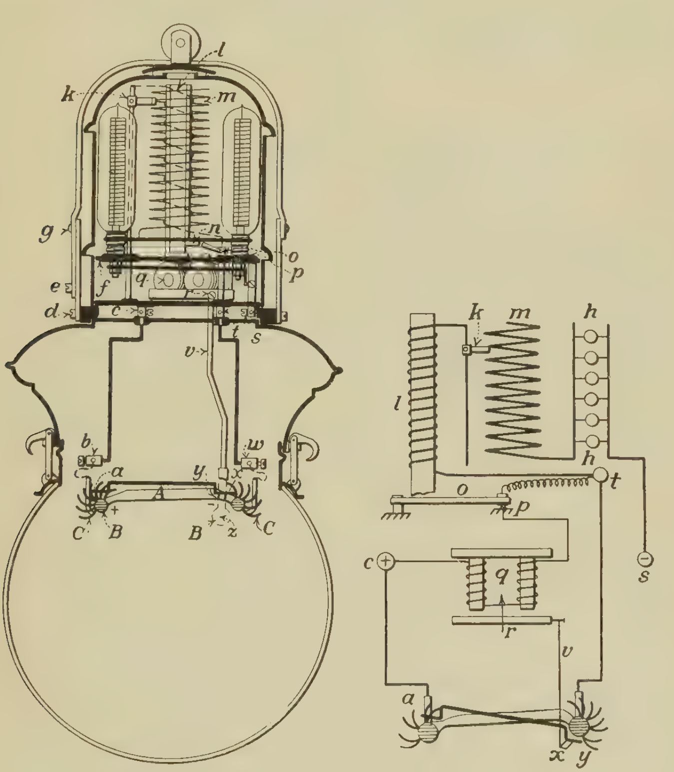


Fig. 133.—The quartz lamp.

The construction of the quartz lamp is shown in Fig. 133. q is the tilting magnet which is cut out by the solenoid l, carrying the inductance, acting on o; h represents the ballast, which consists of iron wires in hydrogen atmosphere. The tube is at A and radiators of metal at C cool the terminals.

The *Moore tube* lamp represents the result of an interesting line of research upon the possibilities of vacuum tubes. This

unit involves the principle of the Geissler tube with small amounts of gases to modify and increase the amount of light.

The first installation of this form of lamp was in Newark, N. J., in 1904, after some 12 years of persistent research on the part of Mr. Moore. It consisted of a glass tube 1¾ in. in diameter and 180 ft. long (Fig. 134). Air, at a pressure of about one-thousandth part of an atmosphere, was in the tube, from which a pale-pink color was obtained. High-voltage (about 16,000 volts) alternating current was supplied by a transformer to two carbon electrodes inside the ends of the tube. The air had to be

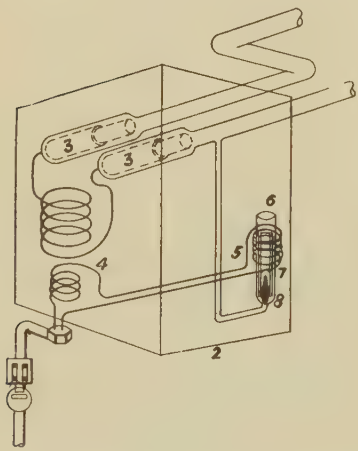


Fig. 134. The Moore tube lamp.

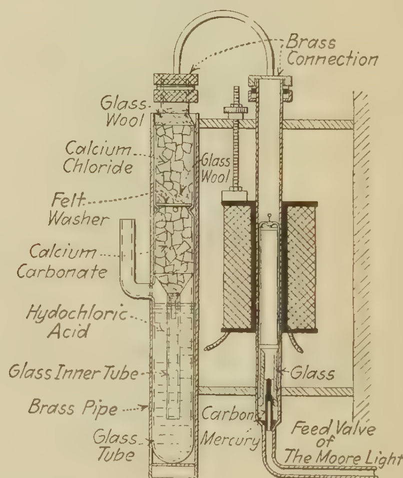


Fig. 135.—Control for Moore tube.

maintained within one ten-thousandth part of atmospheric pressure above or below the normal degree of vacuum, and as the rarefied air in the tube combined chemically with the carbon electrodes it was necessary to devise means to maintain the air in the tube within the narrow limits of this slight pressure.

This was accomplished by means of a feeder valve (Fig. 135), consisting of a piece of carbon through which air could pass but not porous enough to allow mercury to percolate through it. As the air pressure became low, an increase of current passed through the tube, the normal being about $\frac{1}{10}$ amp. This increased the primary current of the transformer. In series with the primary coil was an electromagnet, which lifted, as the current increased, a bundle of iron wires mounted in a glass tube which

floated in the mercury. The glass tube, rising, lowered the height of the mercury, uncovering the carbon rod cemented in a tube connecting the main tube with the open air. Thus, air could seep through the carbon rod till the proper amount was fed into the main tube. When the current came back to normal, the electromagnet lowered the floating glass tube, which raised the mercury and sealed the porous carbon.

Nitrogen gas gave a yellow light and greater efficiency. Nitrogen gas was supplied the tube by removing the oxygen from the air used. This was accomplished by passing the air over phosphorous, which absorbed the oxygen.

Carbon dioxide gas gave a pure-white light but at about half the efficiency of nitrogen. The gas was obtained by allowing hydrochloric acid to come in contact with lumps of marble

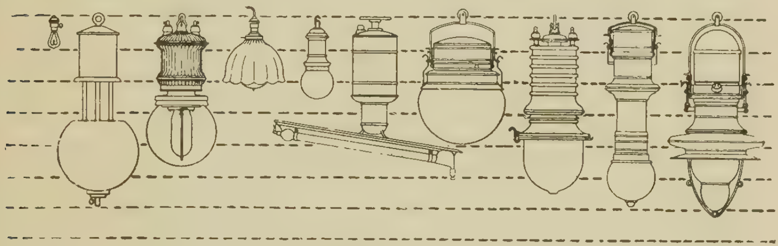


FIG. 136.—Chart showing relative average overall dimensions and appearance of some of the various lamps.

(calcium carbonate), which set free carbon dioxide and water vapor. The latter was absorbed by passing the gas through lumps of calcium chloride. The carbon dioxide tube, on account of its daylight color value, made an excellent light for color matching. A short-tube lamp is made for this purpose and this is the only use which the Moore tube now has, owing to the more efficient and simpler tungsten-filament lamp.

The Moore tube was made in various sizes from 40 to 200 ft. in length. The 200-ft. tube with nitrogen gas had an efficiency of about 10 lumens per watt.

The discovery of *neon* and its use in gaseous conductor lamps made possible a comparatively low-voltage lamp of this type, having a fairly high efficiency. In 1916 the first portable and thoroughly commercial *neon-tube* outfit of high intensity and efficiency operated from a step-up, 60-cycle transformer was exhibited. The tube was in the form of a hairpin and had a

total gas-column length of 101 in. at 7/8-in. diameter. The efficiency was about 17 lumens per watt.

Various alternating-current tube lamps, provided with two similar metal electrodes, have also been made to operate on 220 volts without a transformer, but they used a momentary higher voltage to start the gas-column discharge. This was most simply accomplished by short-circuiting a series inductance. The gas column in this type of lamp was about 3 in. and the discharge could be maintained by 220 volts after being started. The neon plays the same part in the gaseous conductor that the Welsbach mantle or the impregnated-arc-lamp electrode does in heated solids giving a great increase in light. The maximum emission is between wave lengths 0.590 and 0.650 and shows excellent selective radiation.

The general appearance and relative sizes of some of the lamps described in this chapter are shown in Fig. 136.

CHAPTER XI

THE PRINCIPLES OF INTERIOR LIGHTING

An interior illuminating system may very properly be considered a *complex problem*, made up of a number of subordinate problems. The elements to be considered are: the class of room and the service for which the illumination is required; the luminaire best suited for the service; the effect of the color and the reflection of ceilings and walls; together with intensity, distribution, diffusion, color, intrinsic brightness, glare, shadow, and the like.

With these various factors in mind the question arises as to what constitutes the essentials of a *good lighting installation*. Following the order given above, it is easy to formulate a rule which will apply to all but exceptional cases. The *intensity* should be ample to enable one to see clearly and distinctly, and the *distribution* should be such that the illumination over part of the room at least will be nearly uniform. The *light* should be soft and well diffused. The *color* of the light preferable depends upon the class of service and the tastes of the individual. A light approaching daylight in quality or inclined toward the yellow will, in general, be found satisfactory. The *sources of light* should be placed well above the range of vision, their intrinsic brightness reduced by diffusing glassware, and objects capable of high specular reflection removed from the range of vision. *Shadows* are necessary for distinguishing outlines, but such shadows should be toned down and be not too abrupt or dense.

Rooms and Lighting Systems.—As regards interior lighting installations, there are three general types of rooms:

1. *Small rooms*, as those of a residence, or a small office, in which there may be only one lamp or one luminaire.

2. *Long rooms*, comparatively narrow, in which the lamps can be placed in a row running lengthwise of the room, as in hallways or small stores.

3. *Large rooms*, such as are found in large stores, general offices, theaters, churches, auditoriums, etc.

There are also three general systems of illumination for any of these interiors:

1. The *direct system,* where the light from the lamp passes direct to the working plane. The lamp may or may not be equipped with a reflector, shade, or diffusing media.

2. The *semi-indirect system,* where the lamp is equipped with an inverted translucent reflector which lets some of the light pass directly to the working plane while the remainder is thrown to the ceiling or walls, from which part is reflected and in this way reaches the reference plane.

3. The *indirect system,* where efficient opaque reflectors are used and the entire available light thrown to the ceiling, from which the greater part is reflected to the reference plane.

Any of these lighting systems may be used for any of the three classes of interiors, provided conditions are favorable. The semi-indirect and the indirect systems obviously require very light-colored ceilings to be satisfactory.

The Direct Lighting System.—The problem with the small room is to illuminate a certain portion of it to the required intensity. In general, the illumination should be fairly uniform. The relation between the illumination desired and the distribution of light from the source required to produce those results depends upon:

1. The size of the room.
2. The height of the source above the reference plane.

For any given size of room and height of light center, the distribution curve which will give the desired distribution may be easily determined. It is obvious that any given distribution curve will give the same proportionate illumination so long as the relation between the size of the room and the height of the light center is kept constant.

If, now,

$$J = \frac{\text{mean dimension of room}}{\text{height of light center above reference plane}},$$

then for any value of J there is a given distribution curve which will produce the desired distribution of illumination.

The curves of Fig. 137 have been derived to give uniform illumination over certain surfaces for different values of J from 1.5 to 4. Hence, for uniform illumination in a small room having one central luminaire, types of distribution similar to those shown in Fig. 137 are necessary. In practice, however, the diffusing

glassware necessary to lower the intrinsic brightness of the source does not, in general, give distributions similar to these. The reflections from ceiling and walls tend toward greater uniformity and this light together with that from the ordinary luminaire usually gives an illumination sufficiently uniform for practical purposes.

There are on the market reflectors known as the "distributing" or "extensive," the "intensive," and the "focusing" types. The distributing or extensive type is designed for rooms with low

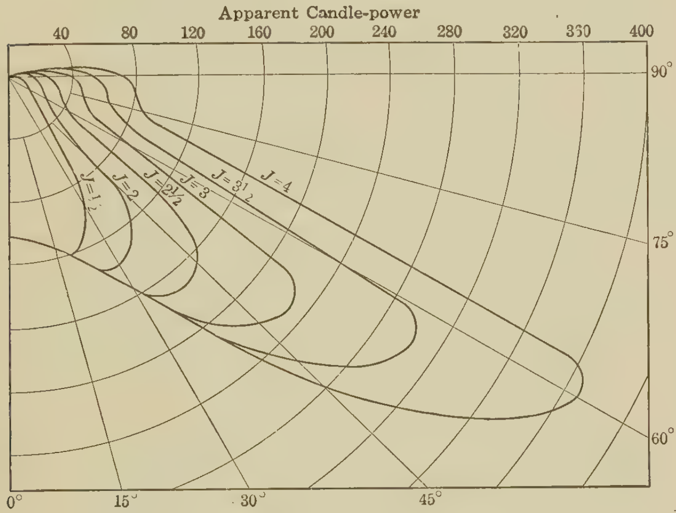


Fig. 137.—Curves for uniform illumination.

ceilings or single-unit installations. Its polar curve is similar to curve $J = 2$ in Fig. 137. The intensive type gives a distribution similar to curve $K = 1\frac{1}{4}$ in Fig. 139. The focusing type for high installations or for high intensity over small areas gives polar curves similar to $K = \frac{4}{5}$ (Fig. 139). The distribution of illumination for each of these units is shown by curves D_1, I_1, and F_1, respectively, of Fig. 140. Curves D_2, I_2, and F_2 show the resulting illumination from two units of each type, when placed as indicated.

Long, Narrow Rooms.—In the lighting of interiors of the second class, or long, comparatively narrow rooms, the area may be divided into squares and each square treated similarly to the small room just described. As will be seen by referring to the

polar curves of the last figure, each lighting unit emits a cone of light which will illuminate a certain area or circle. Placing these units in a row lengthwise of the room, spaced as indicated by Fig. 138, will satisfactorily illuminate this class of interiors.

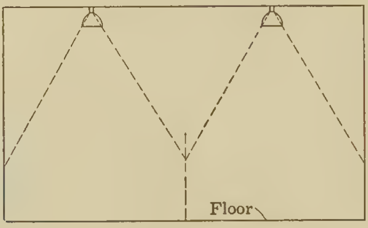


Fig. 138.—Cones of light.

Large Rooms.—The illumination of large interiors offers no particular difficulties. The practice is to determine the style of lighting equipment best suited for the class of service and then, from a study of the conditions, surroundings, etc., calculate the

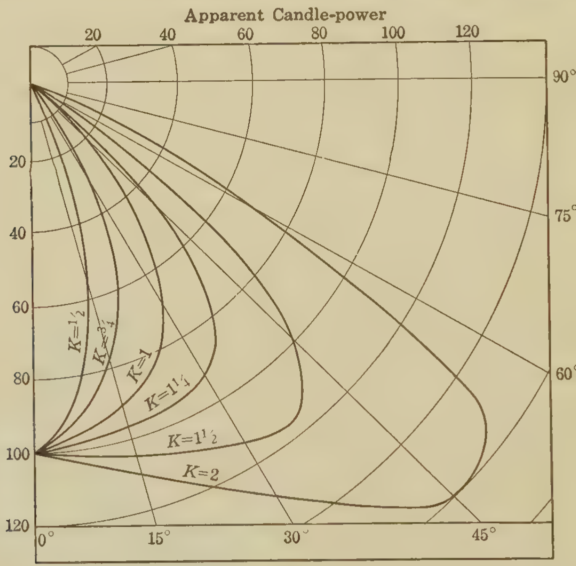


Fig. 139.—Curves to give uniform illumination. (Two or more lamps.)

number of lamps required by some one of the methods taken up in Chap. IX. What is of concern now is the location of the lamps —the height above the reference plane, and the distance between the different units. It has become the practice to divide the

area of the room intó as many equal rectangular sections as there are lamps required, making the sections as near squares as possible, and to place an outlet over the center of each section. If the room is of such dimensions that it can be divided into N equal squares, than the distance d between lamps located above the centers of the squares will be

$$d = \sqrt{\frac{S}{N}}, \tag{85}$$

where S is the area of the room in square feet, N the number of lamps or squares, and d the distance between lamps in feet.

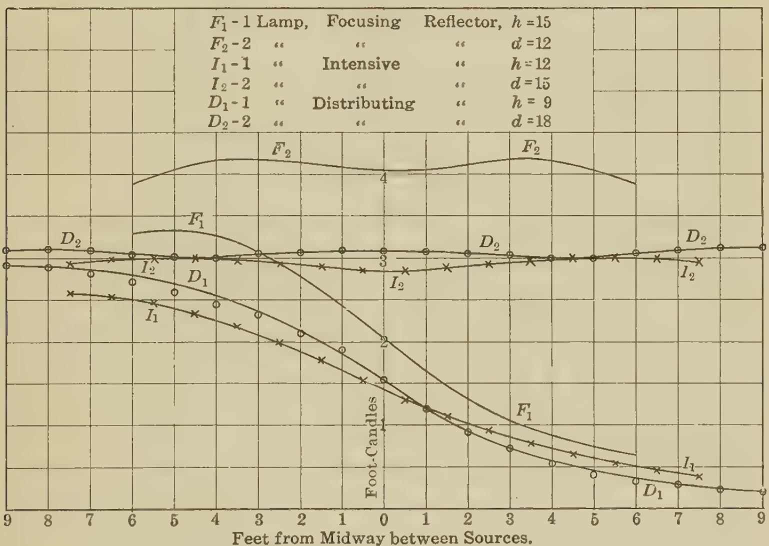


FIG. 140.—Illumination due to one and two 250-watt tungsten lamps equipped with intensive, extensive and focusing types of reflectors.

If the area must be divided into equal rectangles, having the dimensions b and c ft., and a lamp placed above the center of each rectangle, then $b = \frac{S}{cN}$, the distance between lamps in one direction, and $c = \frac{S}{bN}$ the distance in the other direction. The proper methods of spacing the lamps in a room are shown in Figs. 108 and 109. Having settled the question of spacing the light sources, the next item is the height of suspension. Uniform illumination is a good criterion to work for, and with the distance

between lamps established it follows that the *minimum* height of suspension above the reference plane will be determined by the distribution of light from the unit chosen.

Analyzing this phase of the subject, Mr. Sweet[1] derived a set of curves (Fig. 139) showing the different distributions for $\frac{d}{h} = K = \frac{1}{2}, \frac{3}{4}, 1, 1\frac{1}{4}, 1\frac{1}{2}$, and 2. In other words, for uniform illumination, the maximum distance between lamps must not be more than $\frac{1}{2}$, $\frac{3}{4}$, etc. of the height of suspension above the reference plane.

The False Ceiling.—Another class of direct lighting consists in placing the lamps above false ceilings of milk or opal glass, the object being to secure a well-diffused illumination; in this respect it is remarkably successful, but the use of this system is obviously restricted, due to the necessity of the false ceiling, the inconveniences pertaining to renewals or trimming, and to the fact that other systems of either the direct, semi-indirect, or indirect types are found quite as satisfactory.

Skylight System.—Still another method is to place the lamps above the sky windows, when such a system of daylight illumination is practiced. There, of course, the system closely approximates daylight illumination with respect to diffusion and distribution. The results of such an installation are shown in Fig. 170.

The Effect of Height of Suspension of Lamps upon the Intensity of Illumination.—The fact that the intensity of ilumination due to a point source of light varies inversely as the square of the distance between the source of light and the surface illuminated is familiar to everyone. But the significance and the practical application of the relationship existing between the distance from an infinite linear source or an infinite surface source and the intensity of illumination resulting therefrom are realized only by those most vitally interested in or intimately associated with the theory or uses of light.

It has been demonstrated and shown mathematically in Chap. VIII that the illumination at a given point in a normal plane due to a tubular source of infinite length varies inversely as the distance from the source to the point illuminated and not inversely as the square of the distance, as with a point source. It is also well established that the illumination at a point on a

[1] *Trans. Illum. Eng. Soc.*, vol. 4, p. 745.

normal plane due to an infinite surface source is quite independent of the distance between the point and the source.

It is obvious that luminous sources having infinite dimensions are merely theoretical, but it is interesting to assume certain practical conditions and learn how approximately the infinite-dimension relationship may apply in practice. For this purpose the writer has chosen the 100-watt tungsten unit equipped with the intensive type of high-efficiency reflector. This type of reflector is so designed that, when used with the proper lamp and when the units are properly placed, approximately uniform illumination on the working plane will be obtained.

The distribution of light in a vertical plane through the axis of this type of lighting equipment is similar to curve $K = 1\frac{1}{4}$ in Fig. 139. The illumination due to one lamp placed 12 ft. above the reference plane is indicated by curve I_1 of Fig. 140. If two lamps are placed 15 ft. apart and 12 ft. above the plane, the illumination along a line beneath the two lamps will be approximately uniform, as indicated by curve I_2 of Fig. 140. With a distance of 15 ft. between lamps, 12 ft. is the minimum height of suspension which will secure approximately uniform illumination. The two lamps can be placed at greater heights with the same spacing without impairing the uniformity of illumination, although the intensity of illumination will be lower.

To investigate the effect of the height of suspension of lamps above the plane illuminated the writer has assumed a room 75 by 75 ft. in size and lighted by the equipment just described. The lamps are placed, according to common practice, at the centers of equal areas each 15 ft. square in this case, as shown in Fig. 141. The reflection from walls and ceiling is neglected, and the results are calculated from the polar curve by the point-by-point method employing the well-known equation

$$E_h = \frac{I_a \cos^3 a}{h^2}, \tag{73}$$

where E_h = the intensity of illumination on the reference plane.

I_a = the candle power a deg. from the vertical.

h = the height of the lamps above the reference plane.

The illumination at the center of the room was determined for: first, due to one lamp (No. 13), which may be considered a point source also; second, due to a row of lamps (No. 11 to No. 15, inclusive); and, third, due to all of the twenty-five lamps.

The results so calculated with the lamps at different heights are represented graphically in Fig. 142, together with those for

FIG. 141.—Location of 25 lamps in room 75 ft. square.

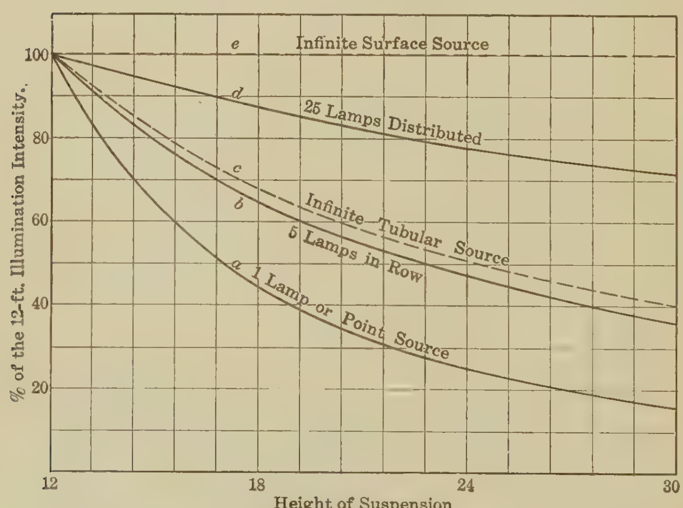


FIG. 142.—Effect of height upon the intensity of illumination.

the theoretical infinite linear and surface sources. The minimum height is 8 ft., the least height for uniform illumination with a

spacing of 10 ft. The maximum height is taken as 30 ft. The uniformity of illumination is approximately the same for all heights from 12 to 30 ft. In this figure the heights at which the lamps are supported are taken as the abscissæ and the intensity, in per cent of that at a height of 12 ft., as ordinates. Curve *a* simply represents the case of one lamp or a point source and the illumination varies in accordance with the inverse-square law. Curve *b* indicates the variation in intensity due to the row of five lamps, showing a considerable departure from the inverse-square law but not a very great difference from the theoretical infinite tubular source represented by curve *c*. Curve *c* is plotted with illumination varying inversely as the height of suspension. Curve *d* represents the intensities due to the twenty-five lamps and curve *e* the ideal case of an infinite surface source.

In interpreting these results it must be borne in mind that the lamps have been raised from 12 to 30 ft., or through a distance of 18 ft. Also no correction has been made for reflection from walls and ceiling. These curves then represent the maximum decrease that may be expected even with dark walls and ceiling. The decrease in intensity of illumination when the lamps are distributively located and are raised to a greater height is obviously due to a greater part of the light passing to the walls and ceiling. If the walls and ceiling are white, about 70 per cent of the light thus apparently lost will be returned to the reference plane and will greatly reduce the difference between curves *d* and *e*. The same line of reasoning will apply to some extent to the other cases as well. Moreover, a little thought will make it clear that, as the lamps are raised, the rays passing to the walls and the ceiling strike those surfaces at angles which are more effective in throwing this light onto the working plane.

Many mistakes are continually being made in the lighting of large rooms by locating the lamps too low. There appears to be an insistency among those "who know not, but think they know," that the proper height at which to locate the lamps of an installation is 10 or 12 ft. above the floor, irrespective of the size of the room, height of ceiling, class of service, or condition of the surroundings. In a large room with the lamps placed at this height, the sources of light are but little above the line of vision, and shine into the eyes when observing objects around the room. In this way the pupil of the eye is contracted and the

illumination is less effective and less satisfactory than if its intensity be perhaps several per cent less but with the lamps placed higher and out of the range of vision.

The Semi-indirect Lighting System.—The semi-indirect system is a combination of the direct and indirect systems, as the name indicates. It may employ some of the translucent reflectors inverted so that the greater part of the light is thrown to the ceiling while more or less passes directly through the reflectors to the reference plane, or translucent reflectors of special design, and possessing artistic and ornamental features, which produce the same results as the inverted reflectors.

These may be of either prismatic or opal glass. The efficiency of this system depends upon the per cent of the light from the source which passes directly through the reflector to the reference plane. With light opal reflectors the working efficiency may be as high as those of the bare lamp, while, on the other hand, if the reflector be surrounded by a translucent holder for æsthetic purposes the per cent of the light flux effective may be less than for the indirect system under the same conditions of ceiling and surroundings.

The Indirect Lighting System.—The indirect systems may be subdivided into:

1. Those where the source of light is located in luminaires supported or suspended in different parts of the room.

2. Those where the lamps are placed in coves or recesses around the sides of the room, and where the luminaires or reflectors are not visible.

In order to use this system, the first requisite is a light-colored ceiling. Pure white is the most efficient reflector and the nearer white the color of the ceiling the more efficient will it be as a reflector. For decorative reasons it is often desirable to introduce some tint to change the color from a pure white. The most efficient tints for this purpose are cream or light pink. Reds, browns, blues, and greens are very inefficient. Even light gray, which is a mixture of black and white, is a poor reflector.

Next after the color of the ceiling comes the question of its surface and contour. For the cove or recess system an arch or dome-shaped ceiling is preferable. The light from the lamps is then thrown from the coves onto these concave surfaces and a better illumination is obtained on the reference plane than if the ceiling be flat.

The most universally applicable indirect system is the one where inverted reflectors in pendent luminaires are placed above the centers of the areas to be lighted. The engineering features of this system have been clearly set forth by Mr. Cravath.[1] This system can be installed in small rooms where the ceiling outlet is located in the center of the ceiling, or in large rooms in the center of bays, the outlets, in general, being located as for direct lighting. In general, the best conditions for this system are the ordinary flat ceilings with a smooth surface. Corrugations in the ceiling tend to lower the efficiency of the system, as do also arches and beams in some cases.

Figure 143 shows a typical case of indirect lighting from a luminaire hung in the center of a small room with a flat ceiling. It represents a cross-section of such a room. An inverted reflector with a lamp in it, located at A, throws a cone of light to the ceiling. Most of the flux of light strikes the ceiling between the points B and C. From B and C to the walls there should be a gradual tapering off of the illumination on the ceiling if a pleasant effect is to be produced. Mostof the flux of light is confined to the center of the ceiling to secure the greatest efficiency.

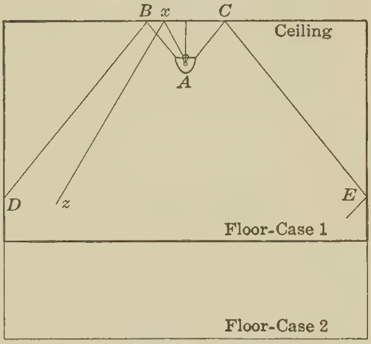


FIG. 143.—Section of room.

For example, the ray Ax in Fig. 143, if reflected from the ceiling at the same angle as its incidence, will take the path xz and reach the working plane in the room directly from the ceiling with only one reflection. On the other hand, rays given off from the lamp and reflector at angles more oblique than the angle of the ray AB would strike the ceiling outside of the area between B and C, and, if regularly reflected—that is, reflected at the same angle as that of incidence—would strike the wall and would necessarily undergo another reflection before reaching the working plane.

In the two cases just noted it was assumed that the ceiling gives "regular" reflection like a mirror, with the angle of incidence equal to the angle of reflection. This assumption is necessarily made for the purpose of arriving approximately at the

[1] *Elec. World*, vol. 57, p. 1172.

correct principles to follow in the design of indirect illumination. As a matter of fact, however, it is known that every calcimined or painted ceiling is not a regular reflector, but an irregular or diffuse reflector. Such ceilings are slightly rough. Each minute portion of the ceiling must be considered as a reflector by itself, and the minute portions are at an infinite number of angles with reference to the general plane of the ceiling.

The effect of diffuse reflection is shown in Fig. 144, where AB represents the plane of the ceiling and SC a beam of light striking the ceiling. If the ceiling were a regular or plane reflector, the beam would be reflected from the ceiling at the same angle as the angle of incidence and would take the path CM. As a matter of fact, it is diffused in various directions, as indicated by the dotted lines. The reflection is more or less semiregular, as indicated in Fig. 3*c*. From these curves it will be seen that, while the ceiling may be far from a regular reflector, still the intensity of the reflected light is a maximum at the angle equal to the angle of incidence. Hence in the theory of indirect illumination design it is proper to consider primarily the regular reflection from the ceiling.

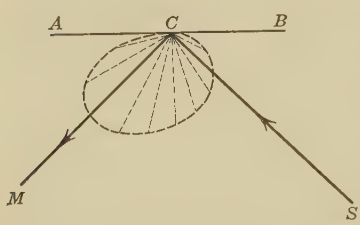


Fig. 144.—Diffuse and regular reflection.

The absence of shadow beneath the luminaire is obviously due to the diffusing properties of the ceiling. If the ceiling were a perfectly plain mirror, it is evident that there would be such a shadow. However, from an inspection of Fig. 144, it is seen that it is impossible for such a shadow to exist, because of the diffuse reflection of the light from all parts of the ceiling surrounding the luminaire outlet. As a matter of fact, the lightest place in the room is the point directly underneath the luminaire, except in rare cases, where a very large bowl type of luminaire is placed too close to the ceiling.

In the lighting of small rooms, say from 10 to 20 ft. square, the common practice for the majority of conditions is to locate an outlet at the center of the ceiling. When planning the lighting of large interiors, the space to be lighted should, if possible, be divided into squares with an outlet at the center of each square, or rectangle, just as with direct lighting. When planning direct

lighting, each lamp is assumed to throw a cone of useful light, which will cover a certain area or circle. For example, the room which is shown in cross-section in Fig. 138 has two direct-lighting units. The cone of light from each covers a certain area. If the reflectors are translucent, considerable light will be given off outside of the cones indicated. The object of the designer of efficient direct illumination, however, is to confine a considerable portion of the flux of light within a certain cone, and to locate the outlets so that the cones will cover the area to be lighted. In practice, in a large interior the cones of light overlap each other and, in fact, considerable overlapping is always desirable on account of the reduction of objectionable shadows.

In planning indirect-lighting installations it must also be remembered that properly designed indirect-lighting units give cones of light just as do direct-lighting units. Thus, in Fig. 143, *BCED* represents the lower part of a cone of light obtained by reflection from the cone *ABC*. The diameter of the base of the cone in Fig. 143 can be increased by lowering the luminaire *A* or decreased by raising the fixture nearer the ceiling. To be sure, there is no well-defined cone in either the direct or the indirect installations referred to, but there are certain limits within which one must work if good results are desired.

Referring again to Fig. 143, the cone of light of which *DE* is the base is just sufficient to cover the working plane with the floor located as in case 1, indicated by the solid line. If the height of the room be so increased that the floor is located as in case 2 (Fig. 143), indicated by the lower line, and if the luminaire be left in the same position relative to the ceiling, it is evident that much more light will be directed to the walls than in case 1. The flux of light striking the wall represents a certain loss, which may be considerably greater than in case 1. Thus it is impossible to light high rooms as efficiently as low rooms by indirect lighting. In case 2 (Fig. 143) better results could be obtained by using a more concentrating reflector, or raising the reflector *A* nearer the ceiling, so as to reduce the diameter of the base of the cone of light so that less may strike the wall.

On account of the diffuse reflection from ceiling and walls it is impossible to control the flux of light very accurately with indirect lighting, and in high narrow rooms the efficiency must necessarily be lower than in low, wide rooms. The same thing

is true with direct lighting, but the light can be more nearly controlled when one is dealing with the reflection from reflectors over lamps than when dealing with diffuse reflection from ceilings.

In a small room better results will be obtained by using a concentrating reflector, while in large rooms the distributing type of reflector will give better satisfaction. The difference due to placing the reflectors at various distances from the ceiling is so small that the general appearance of the installation due to the position of the luminaire and the distribution of the light on the ceiling carry more weight than the difference in light distribution on the working plane due to the several heights of fixture suspensions.

Figure 145 gives the polar candle-power curve from a type of reflector designed for indirect lighting of this character and

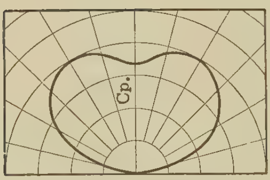


Fig. 145.—Relative distribution of light from a distributing-type indirect reflector.

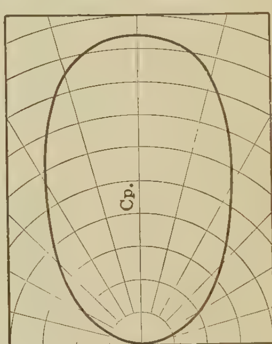


Fig. 146.—Relative distribution of light from a concentrating-type reflector for indirect lighting.

classed as of the distributing type. With this reflector the lamp filament is about even with the top of the reflector and considerable light is given off to light the far corners of small rooms, in which it may be hung in the center. Figure 146 gives the polar candle-power curve of a reflector for similar uses, classed as of the concentrating type. The distribution of light obtained on the working plane with the reflector shown in Fig. 145, under given conditions, is shown in Fig. 147. This curve shows the foot-candle illumination along a radial line, beginning at a point directly underneath the reflector. The test was made in a very large room with a ceiling 13.5 ft. high and the reflector 36 in. from the ceiling. Reflection from surrounding walls, etc., enters into the curve (Fig. 147) to some extent. For the lighting

of a large general office with reflectors of this kind, at the ceiling height mentioned, remarkably uniform illumination can manifestly be obtained by placing lamps at outlets 20 ft. part.

With those types of reflectors the candle-power distribution of which is illustrated in Figs. 145 and 146, the lamp filament is placed vertically within the reflector. It has not been found feasible to design reflectors which will permit spacing of outlets more than 20 ft. apart when very uniform illumination is desired in a large area with ceilings 14 ft. high, although very good results would be obtained with 24-ft. spacing. This is because of the limitations of the cone of light given from a reflector or group of reflectors at a single outlet. For example, the portion of a cone

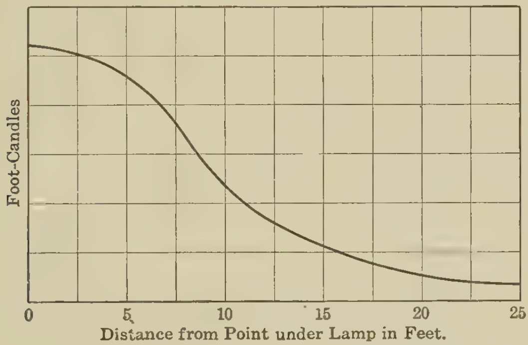


FIG. 147.—Illumination from one lamp (reflector shown in Fig. 145).

indicated by *DBCE* in Fig. 143 represents what might be called the cone of useful light from a reflector of the type of distribution shown in Fig. 145. The cone for Fig. 146 would have a narrower angle. The area of the base of this cone, as before explained, will be dependent on the distance the reflector is hung from the ceiling and on the ceiling height. In order to serve as a rough guide in determining distances of reflectors from ceiling and probable wall losses in various sizes of room, it is well to prepare for each type of reflector used a piece of tracing cloth or transparent celluloid having the angle *ACE* marked upon it. A cross-section of the room should be drawn, for example, as in Fig. 143. Then by laying the angle *ACE* marked on tracing cloth over the cross-section of the room the amount of area that can be covered and the suspension height of the fixture can be determined at once. As before stated, however, considerable latitude can be allowed in fixture height. It is, however, mani-

festly uneconomical to hang a fixture with a distributing type of reflector very low in a high, narrow room.

In the lighting of large interiors with flat ceilings with indirect illumination of this kind a safe general rule is that outlets can be spaced in the centers of 10- to 24-ft. squares if the ceilings are 10 to 14 ft. from the reference plane. With very high ceilings the number of outlets can be considerably reduced. It is simply a question of drawing a cross-section of the room to scale and applying the critical-angle diagram spoken of to determine what the safe procedure may be.

Reflectors.—In order to diffuse the light, lower the intrinsic brightness of the source, and increase the illumination where it is useful, some type of reflector, shade, or diffusing glassware become necessary.

Diffusing and light-directing reflectors on the market at the present time may be classified under two general headings: *viz.*, material and use. The first mentioned may be subdivided into two general classes—steel and glass.

The term *steel reflectors* is commonly applied to those reflectors which have sheet steel as a base, to which is added, to form a reflecting surface, such material as:

1. Porcelain enamel, which is practically a coating of opal glass fired on. This forms a very permanent, durable, efficient, and easily cleaned reflecting surface. This is undoubtedly the most generally used type of steel reflector.

2. Paint enamel, as the name implies, is a coating of enamel paint applied to the reflecting surface. This coating is cheaper than porcelain and when new is quite efficient. It is subject to rapid deterioration when exposed to acid fumes, etc., however, and will not retain its original efficiency after cleanings. The distribution of light is not materially changed by changing the contour of the reflector when this type of reflecting surface is used.

3. The third type of steel reflector is that having an aluminum reflecting surface. An aluminum paint is sprayed on the steel base, forming a reflector of fairly high efficiency. As this surface produces specular reflection, it is possible to vary the distribution of light by changing the contour of the reflector. Aluminum paint is slightly more permanent than paint enamel, but inferior to porcelain enamel.

Reflectors made of *glass* may be divided into three general groups as follows:

1. Opalescent-glass reflectors are found in many designs, the essential difference being contour, ornamentation, and density of glass. The construction consists of glass having an infinite number of small white particles in a solid colloidal state. Reflectors of this type are either blown or pressed. They are translucent, of varying efficiencies, and the transmitted light is, in general, well diffused, the degree of diffusion depending on the quality of glass.

2. Prismatic-glass reflectors are made of clear glass, molded into scientifically designed prisms. Each prism is designed with reference to the position of the light source, and, as a result, almost any desired type of distribution curve may be obtained. Prismatic reflectors also furnish a certain degree of diffusion to the transmitted light.

3. The third type of glass reflectors are those whose reflective properties depend on a silvered coating on the exterior surface of the glass. The clear-glass blank is usually corrugated or ribbed in order to prevent streaky illumination, which might otherwise result. As a mirrored reflecting surface acts by regular reflection, varying light distributions may be obtained from reflectors of different contours.

In analyzing reflector equipment from the standpoint of use, they may be roughly divided into two classes, namely, *industrial* and *decorative.*

The first class is composed largely of direct-lighting steel reflectors. In addition to these, dense opal, prismatic, and mirrored glass, as well as semi-indirect and semi-enclosing units find application in industrial plants, but they are used to a smaller extent.

In industry, protection of the eye, efficiency of light output, effectiveness of light distribution, ease of cleaning, and durability are prime requisites. Artistic appearance of industrial reflectors is not of material importance, and as long as the above requisites are fulfilled any type may be used.

The second classification, namely, decorative reflectors, covers a much broader field. The requirements of lighting installations, where artistic appearance is of importance, must be carefully weighed and an accessory selected which will give the proper balance between appearance and efficiency of output. Efficiency of output must be sacrificed to obtain quality and effect, and it is obvious that there would be a wide range of requirements between

those of a commercial office, where plainly designed, efficient units find application, and those of a handsomely furnished residence, where the lighting fixtures used and the effects produced should be such as to harmonize with the general scheme of decoration.

Luminaires.—The large variety of luminaires on the market may, from the standpoint of good lighting, be divided into five classes according to the way in which they control and diffuse the light. Those types of reflectors which expose the bare lamp filament are ruled out by good illumination principles. The five preferred classes are: (1) enclosing, diffusing, (2) enclosing, light-directing, (3) semi-enclosing, (4) semi-indirect, and (5) totally indirect. Representative units are show on the following pages.

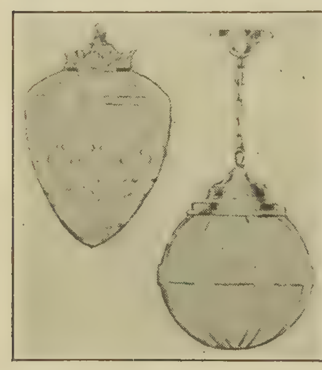


Fig. 148.—Enclosing, diffusing luminaires.

The selection of a particular unit from several of the same general type is largely governed by considerations of efficiency, favorable appearance, and cost. Efficiency must be judged either from authoritative test data or the word and reputation of the manufacturer. An opinion of appearance should be formed after the unit has been seen lighted; frequently, units are made so small that, when used with the size of lamp they are rated to accommodate, they are altogether too bright. A slightly higher first cost should not influence one to decide against equipment which will deliver the greatest satisfaction through the years the lighting system will be in service.

1. Units of the first class have found wide application since the introduction of the type-C lamp. They diffuse the light from high-power sources satisfactorily and may be obtained in a variety of shapes and designs suitable for all classes of interiors.

While diffusing units do not direct light strongly downward, they distribute it in all directions about the interior, make for a bright and inviting appearance of the room, and furnish excellent illumination for high shelves and wall cases. Where walls and ceiling are dark and hence absorb most of the light that strikes them, however, higher-wattage units may be required for satisfactory counter illumination than where light-directing units are employed. Units of ample size and of a good quality of

diffusing glass should be chosen, so that they will not be too bright and so the light will be thoroughly diffused.

2. The need for enclosing units of a type which, while diffusing the light and distributing a satisfactory amount toward the upper walls and ceiling, would also direct more light downward, has been met by the design of so-called enclosing, light-directing units which merit the popularity with which they have been received. They are available in various forms. In some, as shown in *A*, Fig. 149, control of the light is obtained by using translucent glass of uniform density and giving the unit a slightly

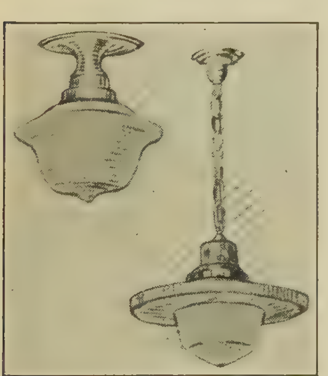


FIG. 149.—Enclosing, light directing luminaires.

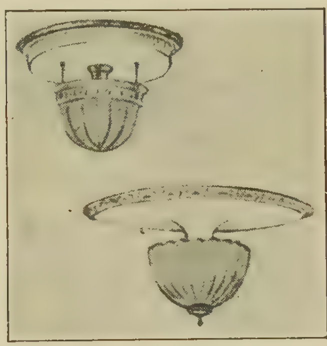


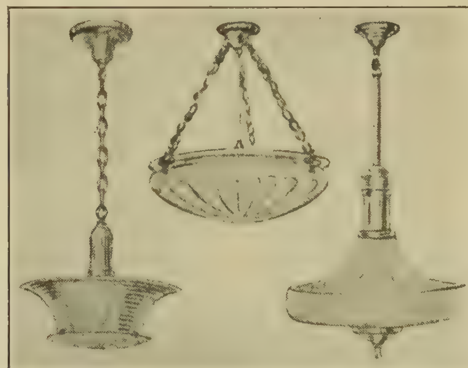
FIG. 150.—Semi-enclosing luminaires.

flattened contour. In others, as in *B*, the upper section is of large diameter and is designed to act as a reflector.

In general, light-directing units furnish less illumination for the upper portions of an interior, including high side shelves and wall cases, than purely diffusing units, but supply more light downward for counter illumination; where walls and ceiling are dark, light-directing units will furnish from 10 to 25 per cent more light upon the working plane.

3. The illumination obtained with this class of units differs but little from that obtained with the enclosing, light-directing type. It is evident, however, that the bowl, opening upward, will invite the accumulation of dust and dirt on reflecting surfaces and that more frequent cleaning will be required than where such surfaces are enclosed. The chief advantage of these units over the totally enclosing type is that they lend themselves somewhat more readily to decorative treatment.

Units of the types illustrated are particularly adapted to mounting close to the ceiling; when suspended from the ceiling the upper reflector will cast a shadow on the ceiling. The softness of such shadows will depend upon the design.



a *b* *c*

Fig. 151.—Semi-indirect luminaires.

4. Where the ceiling and the upper portions of the walls can be finished in light colors and maintained in good reflecting condition semi-indirect units afford pleasing illumination and present an attractive appearance. The light reflected from the ceiling is thoroughly diffused, hence shadows are soft and the units themselves are generally of low brightness. Since light reflected from the ceiling has a pronounced downward direction, the illumination of shelves and wall cases is slightly better with luminaires which direct light more strongly to the sides.

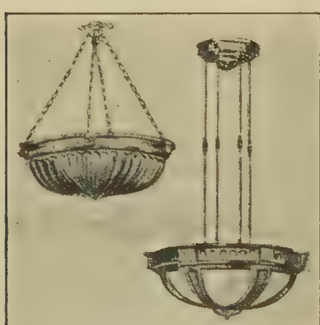


Fig. 152.—Indirect luminaires.

In the types of units illustrated in Fig. 151 *a* and *b*, adequate maintenance is essential to satisfactory results. *c* illustrates a class of totally enclosed semi-indirect units of recent design in which the upper clear-glass portion prevents the accumulation of dust and dirt upon the lamp and reflecting surfaces and greatly facilitates maintenance.

5. Totally indirect lighting is characterized by its softness and freedom from shadow. It is particularly suitable for an interior

in which it is desired to create a subdued and quiet atmosphere. The use of portable lamps, to furnish tone to the lighting and to introduce a certain amount of high light and shadow, is often desirable to supplement indirect lighting in exclusive stores and small specialty shops. Indirect units in which the bowl is luminous are preferred by many.

Light-colored ceilings and upper side walls are essential to the efficiency of a totally indirect lighting system. Since dust and dirt collecting in the indirect bowl seriously reduce the illumination, and since this dust collection may easily escape notice, a regular maintenance schedule is particularly important.

Lighting without Ceiling Luminaires.—During recent years much progress has been made in the lighting of rooms without the use of hanging ceiling luminaires. The results obtained seem to predict that in the future much of the lighting of high-class interiors will be by this system. This does not mean, however, that there are not many interiors in which luminaires are most appropriate and will continue to be used, as, for instance, interiors of the commercial type and those wherein, for certain artistic reasons, the designer wishes to retain the suspended unit.

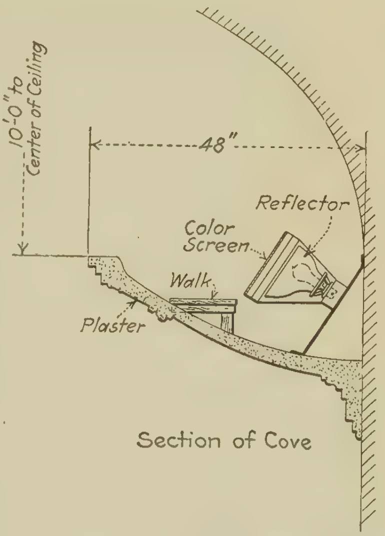


FIG. 153.—Cove lighting detail in the auditorium of the Pantheon Theatre, Chicago.

The methods whereby the illumination of interiors without ceiling luminaires can be accomplished are many. Lighting units may be concealed in projecting coves or cornices; placed in wall boxes or in the caps of columns; hidden in the tops of floor pedestals; and used in art lamps, in display cases, in urns, etc. The characteristics of the individual interior usually suggest the most suitable method.

An illustration of one of the common practices of installing this system is shown in Fig. 153. This installation is in the audito-

rium of the Pantheon Theater in Chicago. Other illustrations follow.

It is often impractical to construct a continuous cove, pocket, or compartment about the room for the concealment of the lighting units, but it may still be desirable to illuminate the interior from hidden reflectors. In such cases especially shaped reflectors in bracket units may be placed directly against the wall or on columns. The light is projected to the ceiling, away from the supporting surface.

This method of bracket lighting is especially suitable for low-ceilinged rooms and for theater auditoriums, where an unobstructed view is desired in all directions. In theaters the usual

FIG. 154.—Side wall luminaires for indirect lighting.

method is to provide wall boxes containing three or four units instead of single units, as shown by the illustration. The units are wired on separate circuits, thus providing several intensities of illumination, adding greatly to the flexibility of the installation.

If pleasing results are to be obtained in the application of the method of lighting without ceiling luminaires, careful planning and cooperation of the illuminating engineer, the architect, and the contractor are necessary. There are numerous instances in which the architectural design and detail have been modified to conform to the lighting plan, but without compromising in any way the decorative and architectural features of the interior. In some cases it may be necessary to design special reflectors in order properly to direct and control the light.

A great variety in lighting effects is possible because of the flexibility of this method. Its applications are almost unlimited in extent. It can be and is used in stores, display rooms, and

offices; in the home and in many other places where, on first thought, ceiling luminaires might be considered the only practical method.

The Basis of Comparison of Illumination Installations and Visual Efficiency.—The reader is cautioned against comparing the direct, semi-indirect, and indirect systems entirely on the basis of the amount of light received on the working plane. The questions of diffusion, distribution, low intrinsic brightness, absence of glare, and low intensity of walls are of utmost importance, and it is well known that these features are secured only by a loss of light. Moreover, the effectiveness of a system of illumination possessing the qualities mentioned above will be

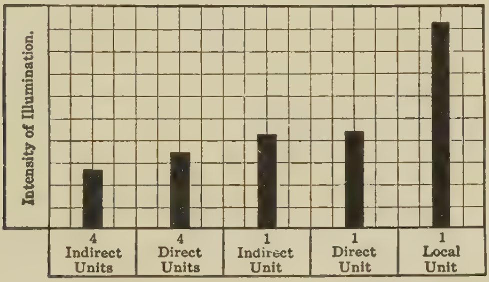


FIG. 155.—Relative average illumination intensities considered the minimum for comfortable reading.

greater than that of another system lacking these qualities, although the intensity of illumination may be much greater in the latter case. Hence a fair and impartial comparison should consist in giving each of the desirable features of an ideal installation a weight comparable with the class of service for which the equipment is to be used.

In line with the foregoing is an investigation by Mr. Cravath,[1] in which he shows that avoidance of glare from glazed paper, with resultant depression of visual function, depends upon deriving the illumination upon the paper from a number of different directions. The relative intensities required for the same degree of visibility with four indirect units, four direct units, one indirect unit, one direct unit, and one local unit are shown in Fig. 155. Thus, for low intensities at least, illumination measure-

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 782.

ments without regard to the other features of the system may lead to erroneous conclusions.

Twilight Illumination.—It is generally recognized by illuminating engineers that the most critical test of a lighting system occurs when it is used to supplement natural illumination. An investigation by Professor Hake[1] indicates that from 30 to 50 per cent greater intensity of artificial illumination may be necessary for satisfactory results during daylight periods than if the lighting is to be used only at night. As an explanation for this, it should be noted the colors of natural and artificial light are not the same, and the resultant illumination is less than the arithmetical sum of the two. Also, by combining the two, a broader spectral distribution results, which may be expected to produce relatively lower visibility.

The 50 per cent increase mentioned above was found to be the average when type-B Mazda lamps were used, while the 30 per cent increase referred to the type-C lamp. Since the color of the light from the former differs more from daylight than does light from the latter, the results are as would be logically expected.

That this greater required illumination is not due to the inability of the eye to adapt itself quickly to artificial light at the close of day is shown by drawing the shades and thereby excluding daylight. If the lighting system is satisfactory at night, it will be found satisfactory with drawn shades, although it may be inadequate before. This suggests the obvious fact that in many commercial installations, where the windows are equipped with shades, the mere lowering of these shades at twilight will often produce quite satisfactory results from an otherwise temporarily inadequate lighting system.

The Effect of Light-colored Ceiling, Walls, and Floor on Illumination.—No matter how carefully designed a lighting system may be as to type and size of lamps, type and make of reflector, spacing, height, etc., if the surroundings are not adapted to reflecting such light as strikes them, then an inefficient system may result. The proper painting of walls and ceilings is, therefore, of great importance.

The ceiling and wall surfaces in a room are secondary sources of light—receiving and reflecting light from the lamps—and merely increasing the reflection coefficient of the ceiling a slight amount may greatly increase the effective illumination.

[1] "Washington University Studies," vol. 10, p. 113.

Illumination tests by Sharp and Millar[1] in a room approximately 12 by 12 ft. and 10 ft. high are summarized below. In this room the ceiling was covered with white cloth. The walls were a grayish-white and the windows covered with manila paper. Black-cloth coverings for ceiling and walls were provided. Screens, light shades, and test plates were also provided, so that the light or illumination at any point in the room due to the source or any reflecting surface, could be measured. The source of light consisted of a 250-watt, bowl-frosted, metallized-filament lamp equipped with a satin-finish, prismatic bowl reflector. It was placed with the lower edge of the reflector 9 ft. 4 in. from the floor. The working plane for the illumination tests was 36 in. from the floor. The results of this series of tests are given in Table 34 and furnish valuable information concerning the action of reflecting surfaces under actual practical conditions.

TABLE 34

Effect of Reflection and Interreflection upon Illumination

Reference Plane Illumination	Lumens
Direct light from source	191
Light from ceiling alone	42
Light from walls by way of ceiling	26
Light from walls alone by way of ceiling	86
Light from ceiling by way of walls	35
Total from different sources on the working plane	380
Total by direct measurement	376
Increase due to light ceiling and walls in per cent	97
Increase due to light ceiling alone in per cent	22
Effective angle light ceiling and medium walls	70°
Effective angle light ceiling, dark walls	50°
Effective angle dark ceiling and walls	45°
Ceiling Illumination	Lumens
Direct from light source	183
Light from ceiling reflected back by walls	20
Wall light reflected by walls	77
Total flux on ceiling	280

[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 391.

TABLE 34.—*Continued*

Wall Illumination	Lumens
Direct from light source	382
Ceiling light from ceiling	116
Wall light reflected by walls	104
Ceiling *via* walls and walls *via* ceiling	70
Total flux on walls	672

Summation	Lumens
Direct light flux upon ceiling	183
Direct light flux upon walls	382
Direct light flux upon reference plane	191
Total light flux direct from the lamp	756
Total light flux calculated from distribution curve of the light source	779
Total effective light flux upon ceiling	280
Total effective light flux upon walls	672
Total effective light flux upon reference plane	380
Total effective lumens	1332
Total reflected by ceiling (42+26+35+116)	219
Total reflected by walls (86+35+20+77)	218
Reflecting coefficient of ceiling (219/280)	78 per cent.
Reflecting coefficient of walls (218/672)	32 per cent.
Ratio of the effective light flux on the reference plane to the amount received direct from the lamp (380/191)	1.99

In very large rooms the question of reflection from the walls becomes of much less importance, since the increase in illumination due to distant lamps will about counterbalance that due to light walls in small and medium-size rooms. The reflection from the ceiling remains and the light thus reflected has a tendency to make the illumination more uniform.

Finish of Ceilings and Walls.—It is therefore important, from economical considerations, to have the ceiling as light in color as practicable. White is usually to be preferred, although if a tint is artistically demanded it should be of a faint cream color rather than of a gray or similar shade. A flat or mat finish is desirable for greater diffusion and the reduction of glare.

There is little difference in the reflecting power of good white fresh paints. The permanency, however, is quite different, as will be seen from Table 35, which gives the results of laboratory tests.

TABLE 35

Paint	Coefficient of reflection	
	New	After aging 1 year
White lead and oil	0.83	0.75
Lithopone	0.86	0.80
Calcimine type	0.82	0.75
Flat enamel (magnesia-bearing)	0.85	0.82
Gloss enamel	0.83	0.83

The decrease in the reflection coefficient of calcimine is due largely to its porous nature, which permits it to absorb dirt readily. The decrease for both calcimine and white lead and oil is progressive. The slight decrease for flat enamel occurs during the first few weeks. Gloss enamel, while permanent, is objectionable because of specular reflections. Flat enamel overcomes this objection and is easy to clean.

The most permanent and highest practical coefficient of reflection and diffusion can be obtained with plaster surfaces treated as follows:

First coat—good impervious surfacer.
Second coat—straight lithopone paint.
Third coat—gloss enamel and lithopone mixed equal parts.
Fourth coat—flat enamel (magnesium-bearing) flowed on.

For metal surfaces, apply a first coat of red lead thinned with raw linseed oil and a drier and turpentine. Over this a coat of lithopone, mixed 1 gal. to 1 qt. of good varnish; then the second, third, and fourth coats as applied to the plaster.

The walls should be of lower reflection power, although the finish may be permanent. A simple painting formula is: A first coat of a good impervious surfacer mixed with equal amount of lithopone paint, a second and third coat of straight lithopone, the last coat tinted with japan tint, thinned with turpentine.

With most systems of lighting a considerable portion of the flux strikes the upper part of the walls, so these also should be of a

light tint. The lower area may well be of a darker neutral color to provide space on which the eye can rest in comfort.

A light-colored room is much more cheerful than one finished in dark paint. In many cases dark surroundings have given the impression of bad lighting, while in reality there was a high enough intensity on the work. The psychological effect of gloomy interiors is well known.

Light surroundings, in general, reduce the conditions of glare. An artificial light source viewed against a bright ceiling is less annoying than in other positions. Light-colored walls diffuse the light back toward the side of the room with windows, which lessens the contrast between the bright sky and adjacent walls.

Light-buff window shades are desirable, and if these are drawn at night they materially assist in reflecting the light rather than allowing it to escape to the street. If these shades are slightly translucent, they are useful in the daytime in cutting down the direct sunlight, diffusing the light which passes through them, and preventing a sharp line of shadow demarcation, which may result if opaque shades are used.

It is rather difficult to tabulate the *reflection factors* for various colors. A number of elements create this condition. There is no standard terminology of paint colors. A tint which one manufacturer may call ivory-tan may be quite different in appearance and in reflecting properties from some other maker's color under the same name. The chemical composition or the method of mixing the paint will have an effect on its ability to reflect light. A higher or lower oil content, for example, produces slight variation.

The most feasible means of presenting the necessary data seems to be to tabulate a number of commonly used colors under a rather broad classification and give a range in percentage for any particular color.

The figures presented in Table 36 are the results of a considerable number of tests by different authorities and are representative average values.

Table 36

Reflection Factors

Color	Percentage of Light Reflected
White—new	82 to 89
White—old	75 to 85
Cream	62 to 80
Buff	49 to 66
Ivory	73 to 78
Gray	17 to 63[1]
Light green	48 to 75
Dark green	11 to 25
Light blue	34 to 61
Pink	36 to 61
Dark red	13 to 30
Yellow	61 to 75
Dark tan	30 to 46
Natural wood brown stain	17 to 29
Light wood varnish	42 to 49

[1] Grays vary remarkably, depending on the way they are prepared. A gray made by mixing lampblack with white paint has a low coefficient of reflection. A gray made by mixing red and green paint with a white base has a relatively high coefficient of reflection. It is known as a warm gray in this case.

Maintenance.—A lighting system requires frequent inspection and cleaning. If it does not receive this attention, the illumination may become inadequate, and the engineer who designed the system is liable to be blamed and his judgment criticized. The depreciation of the lighting system may be *inherent* or *acquired.*

As the tungsten lamp is burned, small particles of tungsten are evaporated from the filament and collect on the lamp bulb in the form of a fine, dark deposit. In the type-C lamp the gas currents carry these particles to the upper part of the bulb, where they are less effective in absorbing light than when deposited opposite the filament. Nevertheless, any accumulation on the interior surface of the bulb absorbs light, and blackened lamps should, of course, be replaced. It is comparatively simple to figure out the most economic point at which to replace lamps, taking into account the price of lamps and the cost of current.

Not only does a black deposit occur on the inside of the lamp bulb, but dust collects on the outer surface. This accumulation cuts down the light from the lamp and should be removed at the

time reflectors are cleaned. This is often more serious than realized.

It is also important to use lamps of the *proper voltage*. While initially the installation may be correct as to voltage, on replacing or ordering additional lamps an error may be made in specifying their voltage. Lamps are designed to operate at the voltage indicated on the label. This voltage rating takes into account renewal and energy costs. If the circuit voltage is appreciably higher than the label voltage, the result will be a short lamp life. If the voltage at the socket is considerably lower than that indicated on the label of the lamp in use, it will not emit the proper quantity of light. To make up for this loss of illumination, it would be necessary to install additional lamps. For instance, seven lamps operating at rated efficiency will give an amount of light equivalent to eight lamps operating 4 volts below the rated efficiency of the lamps. Before ordering lamps it is desirable to determine what average voltage is actually attained at the socket. Where the voltage of the system fluctuates during the day, or where it varies in different parts of the installation, it is proper to order lamps as near the average of this variation as possible.

All lamps and reflectors should be regularly washed and cleaned. The period between cleanings will vary with locality and type of equipment. Obviously, a steel direct-lighting reflector will not depreciate so rapidly as an indirect unit. The under surface of the reflector of the former offers very little opportunity for dust to gather, and that on the lamp bulb will be the primary cause of loss. With the inverted unit, however, a thin layer of dust soon settles on the entire reflecting surface, as well as on the lamp, which will reduce the light output appreciably in a very short time. Not only is this true, but the very arrangement of parts makes the accumulation greater. With the direct-lighting equipment, the reflector itself shields the lamp from falling particles, while they enter directly into the inverted unit.

In order to cover a range of conditions as regards depreciation of equipment due to dirt and dust, two different locations were selected in the city of Cleveland. Samples of lighting equipment commonly used for industrial, office, and store lighting practice were operated under service conditions in these locations following the plan outlined on the following page.

Location A.—The test area was in a factory warehouse adjoining a room carrying on lamp-manufacturing work. Washed air was furnished to a part of the factory, which accounted for the slow depreciation of the lighting units. The dust encountered here was fairly dry and of a fine, powdery nature. The space was steam-heated in winter and the windows were open part of the time, as is usual in a place of this character. Eighteen types of commercial, office, and store lighting luminaires, including open direct, enclosing, semi-enclosing, semi-indirect, and indirect types, were installed for test in location *A*. There were two samples of each type and the entire group was tested for two different periods of 120 days each. Thus it was possible to obtain a result for any one type of unit representing the average of four individual depreciation tests.

Location B.—The equipment at this location was installed on the top floor of a twelve-story downtown building. This location is typical of the usual city office building in a downtown district burning soft coal. There was more oily, sooty dust here than at location *A*. Twenty types of lighting units were tested, including open direct, semi-enclosing, enclosing, semi-indirect, and indirect.

Extreme care was exercised in handling the equipment so that no dust and dirt would be shaken off. In fact, the final figures for the equipment removed for rating during test averaged practically the same as those for the luminaires that were allowed to hang throughout the test without handling. The actual depreciation of the lighting equipment as affected by location and equipment design is given in Tables 37 and 38.

The condition of *walls and ceilings* is very important. No matter how carefully painted a room may be, soot, smoke, and other agencies soon darken the surfaces of the room and cause it to lose considerable of its reflecting power. Any porous paint, such as calcimine or whitewash, is particularly susceptible to this effect. In industrial localities it is frequently necessary, if maximum economy of lighting is to be obtained, to paint the ceilings every year and a half and side walls every three years. A test, to determine the reflection coefficient of the ceiling and walls at frequent intervals, may save considerable on the lighting bill. In general, paint is far cheaper than electrical energy, and in dirty plants painting or cleaning is especially important.

Haphazard cleaning has not usually been found satisfactory, since the accumulation is so gradual that it is not readily noticed by those responsible. Much better success has been secured by organized cleaning, at stated intervals, under the charge of a maintenance department where one person is absolutely responsi-

TABLE 37

Direct-lighting Units

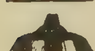
	Description	Actual depreciation	
		Location *A* 120 days dry, fine dust	Location *B* 49 days oily, sooty dust
	Light-density opal glass—clear lamp..	....	10.9
	Light-density opal glass—bowl-enameled lamp..........................	....	25.5
	Dense opal glass—clear lamp........	11.2	
	Prismatic glass—clear lamp..........	12.4	17.3
	Prismatic glass—bowl-enameled lamp.	....	30.4
	Deep enameled steel bowl—clear lamp.	11.5	
	RLM dome—clear lamp.............	12.8	
	RLM dome—bowl-enameled lamp....	16.3	
	Diffusing globe and enameled-steel reflector........................	22.9	
	Diffusing globe—no vent...........	13.4	15.3
	Diffusing globe—bottom vent........	22.7	27.9
	Diffusing globe—top and bottom vent	22.1	
	Frosted ball—top and bottom open...	15.0	
	Semi-enclosing opal bowl with diffusing plate.......................	27.2	33.4

TABLE 38

Indirect and Semi-indirect Lighting Units

Description	Actual depreciation	
	Location *A* 120 days dry, fine dust	Location *B* 49 days oily, sooty dust
Open Type		
 Dense opal bowl	22.5	50.8
 Light-density opal bowl	....	36.3
 Enameled-metal reflector with opal glass bottom	26.0	25.9
 Mirrored-glass bow	26.2	40.7
Closed Type		
 Clear top with bottom opening	35.6	24.0
 Clear top without bottom opening	15.0	
 Prismatic, without bottom opening	10.1	

ble for this. As pointed out before, the periods between cleaning will vary with the locality and with the equipment. Considering average conditions and typical equipment, the fixtures in an office should be wiped out at least once every month, and removed for careful washing once every 3 or 4 months. In the foundry it is probably necessary to clean fixtures carefully once each week.

The shaded areas in Fig. 156 show the percentage loss in light for different cleaning periods for a semi-indirect unit under conditions producing 40 per cent depreciation in 20 weeks. Figure 157 shows the results of the calculations referred to above, assuming the cost of cleaning as 10 cts. for the semi-indirect unit, an energy cost of 5 cts. per kilowatt-hour, average operation of 6 hr. a day, and 200-watt lamps in use.

The two curves are seen to cross at a point slightly beyond the 3-week period; therefore, any cleaning period greater than this value represents an actual loss indicated by the distance between the two curves for the particular conditions under consideration.

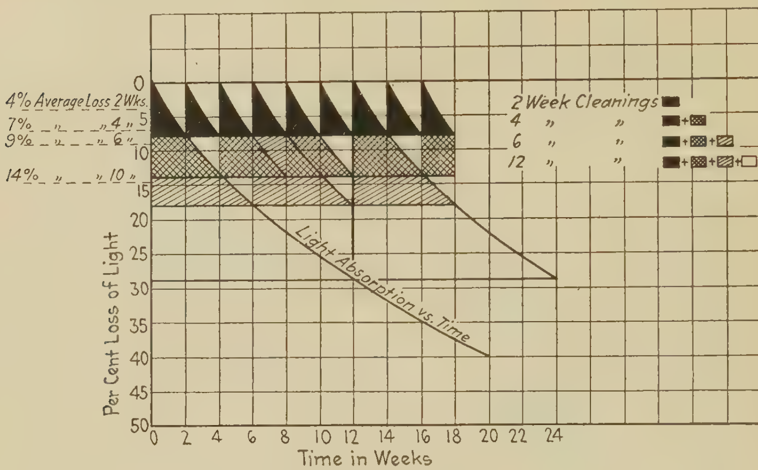


FIG. 156.—Curves showing light absorption due to dust accumulation on lamp and reflector.

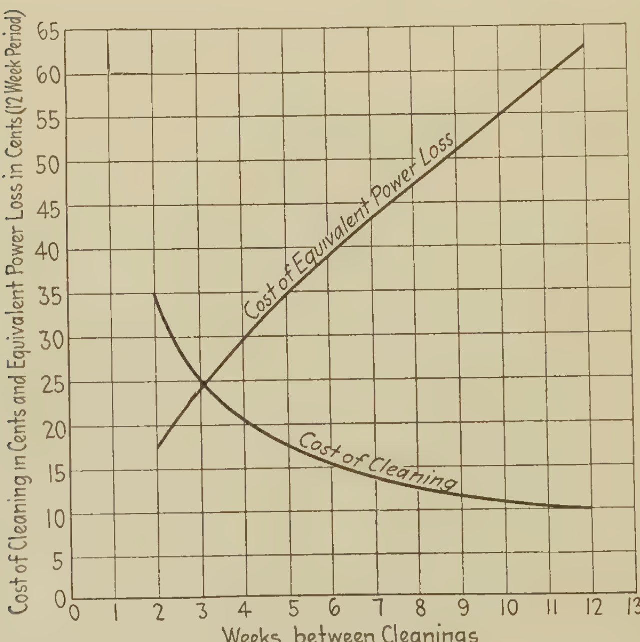


FIG. 157.—Typical relation of cost of cleaning to loss of light.

For cleaning dry dirt, wiping with a dry cloth or brush, then with a damp cloth, and finally drying all surfaces will prove satisfactory. Greasy or wet accumulations on any type of reflector must be removed by washing. Soap and water are good agents, but the film of soap must be removed by rinsing thoroughly, as dried soap accumulates dust rapidly. There are a number of cleaners on the market, but they should be carefully tested to see that they are so smooth as not to make microscopic scratches on the glass, and not leave a film of cleaning material

CHAPTER XII

RESIDENCE LIGHTING AND LIGHTING INTERIORS OF A PUBLIC NATURE

This and the following three chapters will consider a few typical installations of diversified character which represent prevailing practice. When studying these installations the reader should keep constantly in mind those features of the system

FIG. 158.—A few styles of portable lamps for the living room.

which go to make good illumination as outlined in the previous chapter, together with the class of service for which the system is designed.

The Living Room.—In this room many recreations are enjoyed. It is the scene of the social life of the home, and the lighting of such a room should receive special attention. Reading requires more light than talking, but music is more enjoyable in what

is known as a "half light." If, then, the room is to be softly lighted by decorative table lamps, with the help of wall brackets, a general atmosphere of quiet contentment may be produced, the portable lamps furnishing illumination for those reading beside them. For a comfortable game of bridge, it is a necessity that each player be able to see his cards easily, without holding his hand to avoid shadows. The most efficient way to furnish

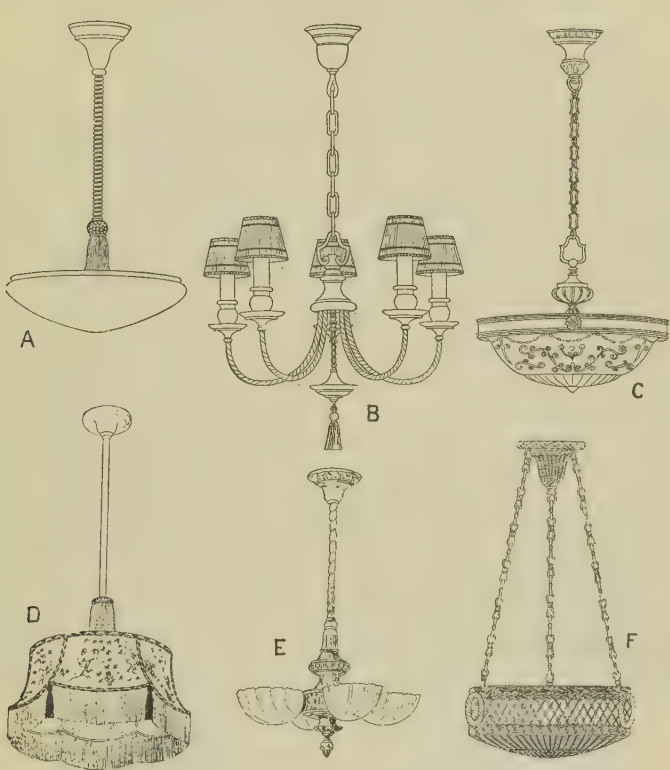


Fig. 159.—A few styles of direct, semi-indirect and indirect ceiling luminaires suitable for the living room under various conditions.

equal light for all is to make use of a ceiling luminaire of the semi-indirect type, which will light the whole room to an even intensity. The advantages of variable lighting are readily appreciated.

There are innumerable period styles of luminaires suitable for the living room. A few typical examples are indicated in the accompanying sketches (Figs. 158 and 159). In choosing luminaires of this nature, the cardinal points in regard to distribution

of light, contrast, and direct glare must be kept in mind. Very rarely is it feasible to use lamps without some sort of a shade or diffusing media. Figure 160 shows the colonial-type direct luminaire, where small, diffusing shades fulfil the requirements outlined above.

With a suitable number of wall and convenience outlets it is good practice to light the living room without a central or ceiling luminaire, and, in this event, table and floor lamps may be used to advantage.

Fig. 160.—A living room showing recent practice.

Figure 162 shows how it is possible to light a room without ceiling luminaires. Large mirrored-glass reflectors in the table and floor lamps direct the light to the ceiling, making it possible to illuminate the whole room without its unity being broken by anything hanging from the ceiling. Small lamps are used to light the shades and furnish some direct light. A number of lighting effects are possible in this room as follows: the wall brackets alone, the indirect units alone, the direct lamps in portables alone, and combinations of any of these. Sheets of

colored gelatin may be laid across the inverted reflectors, toning the color of light as desired.

In choosing portable lamps, particular thought should be given to the shades. It is always objectionable to be forced to

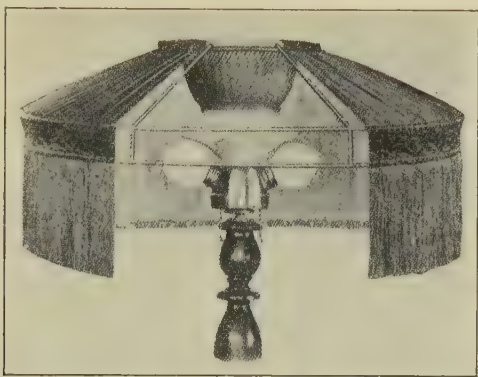


Fig. 161.—Either decorative local lighting or comfortable indirect illumination or both by the pull of a switch.

look at a lamp, and the shades must conceal the light sources from one sitting near them. The materials used should be dense enough so that the filaments do not show through and,

Fig. 162.—Use of the adapter shown in Fig. 161 in lighting a living room.

as pointed out before, it is always desirable to use diffusing bulb lamps in any direct luminaire. With skilful selection, a shade will become an integral part of the color scheme of the room in

the evening, as it is during the day. Sometimes, however, a color harmonizes well enough with the draperies and furniture covering, but when the shade is lighted the effect is far from desirable. This danger is most common with green or blue color schemes. The best solution for such a condition is to have the exterior layer of particularly thin material, such as chiffon or georgette crepe, and the lining a rather heavy rose, buff, or cream. The resultant light will be toned by the lining, and ghastly effects will be eliminated.

FIG. 163.—Dining room and living room lighted with semi-indirect bowls and wall lamps.

A wall switch is most desirable for controlling the lights in the living room, and it is generally advisable to have the central outlet and wall brackets on separate circuits.

The Dining Room.—This room has lighting requirements peculiar to itself; rarely is it used as anything but a place to eat. The interest, therefore, is primarily centered on the table, and this interest may be increased by having the table lighted to a higher intensity than the rest of the room.

The choice of the method by which the dining room shall be lighted—whether by direct or by indirect methods—is a matter

of personal taste. The old-style dome, while often crude and inartistic, provided a most desirable distribution of light. The table was the brightest spot in the room, yet enough light was transmitted through the glass to illuminate the corners of the room, preventing too great a contrast. Several requirements must be fulfilled where a dome is employed. It must be hung high enough that one can see the person on the opposite side of the table, and yet not so high that the lamps are visible. The satisfaction of these requirements will bring the bottom of the

FIG. 164.—Dining room with two lighting systems.

dome about 56 in. above the floor. A dome can often be made more effective by using a small direct-lighting reflector inside of the fabric or glass to send the light downward and conceal the lamp from view.

Some people prefer the room more uniformly illuminated, and this can be accomplished by the semi-indirect system. By choosing the proper density of glass, a suitable amount of light will be transmitted, the table receiving more light than the surroundings.

The Den or Sewing Room.—The lighting requirements of these two rooms are so similar that they can well be discussed together. For close work, either in sewing or keeping records, a high intensity of illumination is necessary. For ordinary purposes, however, it is not desirable to have the whole room as light as this. A combination of lighting is desirable—a central diffusing luminaire to furnish general illumination of moderate intensity, and a portable luminaire for the close work. An excellent type of adjustable luminaire for sewing at night is shown in Fig. 160. This may utilize a 150-watt type-C lamp and a dense blue-glass color screen to produce artificial daylight. On the portable luminaire, it is desirable to use a metal or very dense glass reflector, large enough to conceal the lamp from view. Diffusing bulb lamps prevent disagreeable reflections.

The Schoolroom.—It is extremely important to protect the eyesight of the growing child, for injury to the eye can never be thoroughly repaired.

Daylight Illumination.—One of the fundamental rules for the proper lighting of desks is to have the preponderance of light come from the left side. For this reason many school authorities advocate *unilateral* lighting, that is, lighting by windows located on one side of the room only, especially for classrooms. This method of lighting (see Fig. 165) is recommended where the rooms do not exceed about 24 ft. in width, with windows about 12 ft. high. If the rooms are much wider than this, bilateral lighting, that is, lighting by windows located on two sides of the room, may be required in order to provide sufficient illumination in every part of the room and at the same time to prevent too great a diversity of contrast in the intensity of light on the work spaces.

To secure the highest lighting value, it is recommended that the room be so designed that no working location is farther distant from a window than one and one-half times the distance of the top of the window from the floor.

Windows at the left and rear, where practicable, are preferable to those on the left and right sides of the room, because of the cross-shadows created by the latter arrangement. Lighting by overhead sources of natural illumination although sometimes used for assembly rooms, auditoriums, and libraries, with relatively high ceilings, has ordinarily little application in classrooms and has found little favor in practice.

The sky, as seen through a window, is a source of glare, and so the seating arrangements should always be such that the occupants (pupils) of the room do not face the windows.

Tests of daylight in well-lighted school buildings indicate that, in general, the glass area does not fall below 20 per cent of the floor area.

As the upper part of the window is more effective in lighting the interior than the lower part, it is recommended that the windows extend as close to the ceiling as practicable.

FIG. 165.—School-room lighting with the indirect system.

The lighting value of a window at any given location in the room will depend upon the brightness of the sky, the amount of sky visible through the window at the given location in the room, and, indirectly, upon the reflection factor of the surroundings and the dimensions of the room.

Observations in well-lighted schoolrooms having a comparatively unobstructed horizon show that under normal conditions of daylight satisfactory illumination is usually obtained when the visible sky subtends a minimum vertical angle of 5 deg. at any work point of the room.

Where the horizon is obstructed, as by adjacent high buildings or by high trees, provision should be made for a larger window area than would otherwise be required; also, if need be, for redirecting the light into the room by means of prismatic glass in the upper sashes of the windows, or by prismed canopies outside of the windows.

Although direct sunlight in interiors is desirable from a hygienic standpoint, it is often necessary to excluse or diffuse it by means of shades. These shades should perform several functions, namely, the diffusion of direct sunlight, the control of illumination to secure reasonable uniformity, the elimination of glare from the visible sky, and the elimination of glare from the blackboards wherever possible. These requirements make it desirable to equip each window, especially in classrooms, with two shades operated by double rollers placed near the level of the meeting rail. The window shades may thus be raised or lowered from the middle, thus providing the maximum elasticity for shading and diffusing the light. The shades should be preferably of yellow material that is sufficiently translucent to transmit a considerable percentage of the light, while at the same time diffusing it.

Artificial lighting should be provided for all schools. Although the majority of schools are not used at night, it is essential that artificial light be available for supplementing daylight on dark days. The method of securing this additional light should be given careful consideration. It is self-evident that the proper amount of light must be supplied for any kind of work. The correct intensity is necessary in order that everything which is to be seen may be seen clearly and without fatigue.

A distinction must be drawn between those classrooms which are used for clerical work, reading, writing, etc., and those used for sewing, art, metal work, drafting, chemical experiments, and the like. The latter rooms should be illuminated to the higher values for such work. Even though adequate light can be supplied for any process, it is inadvisable to allow the young child to do fine needlework under artificial illumination. The periods can be so planned that this work can be carried on by daylight.

In most interiors outlets are spaced symmetrically throughout the room, but in the schoolroom the shadow effect is important, so the maximum light should come slightly forward and from the left to diminish the head and hand shadows; as far as possible

the direction of daylight should be imitated, sometimes much improved. A system of general illumination should be used and the lamps hung as high as possible, providing almost uniform lighting throughout the room; in fact, there is a much less variation in intensity across a room than is possible with natural lighting from windows as ordinarily placed. It simulates daylight, makes the room appear much brighter than local lighting, is, in general, independent of the arrangement of furniture, and, without question, is the system best suited for schoolroom lighting. The wiring cost is much lower, there is less likelihood of glare, and there is no danger of the breakage of lamps or reflectors.

As there is a likelihood of glaring reflections from *blackboards*, they should, therefore, always have matt rather than polished

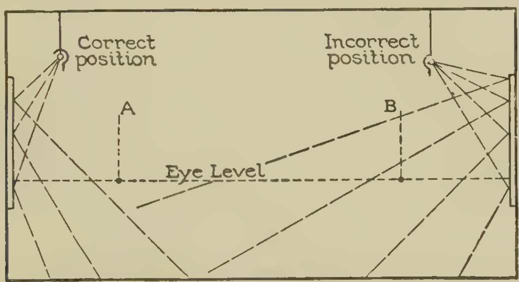


Fig. 166.—Showing how an incorrectly placed fixture may result in annoying specular reflections.

surfaces. It is sometimes possible to prevent this reflection by tilting the boards slightly. Blackboards which will be written on with colored chalks, and those that are more than 20 ft. away from the pupil, should be especially lighted to an intensity approximately 60 per cent higher than the intensity in the rest of the room. This can be accomplished by the use of properly screened and judiciously placed local units (Fig. 166). For clear vision, blackboards should not be located between windows. In order to avoid excessive brightness contrast, which is trying to the eye, they should not be placed on white or highly reflecting walls.

Libraries.—Libraries may be divided into two quite distinct classes—one, the monumental building of the large city, where the rooms are spacious, ceilings high, corridors handsomely finished in marble, and where the element of decoration plays a large part. Reading rooms in this class of building are generally separate from the stack room. The other type is the branch, public

school, or town library, unpretentious in nature, where the books are stored in cases around the room. Here the decorative feature is secondary and utility of light plays a more important part.

It is quiet common practice to install decorative luminaires in the high-ceilinged reading rooms of the first-mentioned class of buildings. These supply a moderate intensity of general illumination, necessary for supervision, and prevent severe contrasts of brightness, but are seldom designed to supply enough light for continued reading. Earnest cooperation between the architect, fixture specialist, and illuminating engineer is advisable.

Fig. 167.—Night view of the Library at the University of Michigan. General illumination furnished by 100-watt Mazda C lamps in mirrored glass reflectors on 4-foot centers on the tops of the book cases. The light cream ceiling reflects well and the result is diffused, shadowless illumination.

The lighting in the library shown in Fig. 167 is an excellent example of the principle of cooperation just mentioned. Indirect illumination, as used in this room, offers certain advantages in reducing reflections from polished tabletops and providing good illumination on vertical surfaces, such as shelves and files, without the use of special lamps. The absence of hanging ceiling fixtures makes this particular installation especially effective and gives the room an appearance of spaciousness. When the units are placed on the tops of the bookcases, they are easily accessible, thus making maintenance a simple matter; with cleanliness, the efficiency of the installation can be retained.

In addition to the general illumination of from 2 to 4 foot-candles, local lighting should be supplied on the tables. These lamps should be carefully chosen, so placed and of such a character that direct or reflected glare is minimized.

In many respects proper table lighting is an economy, producing a high intensity over the working area while a lower intensity is sufficient in the rest of the room. This is particularly important in the library at night, when but few readers are likely to be present. Each reader will then control his own local illumination and the attention will be concentrated upon the work.

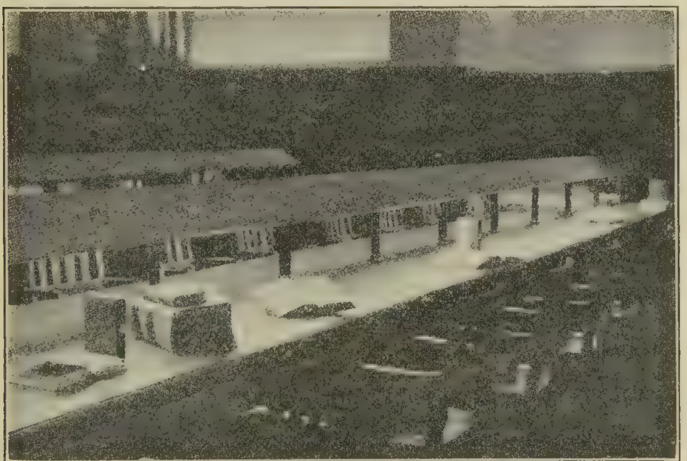


Fig. 168.—Night view of one of the reading tables in the library shown in Fig. 167. A special fixture in the form of a continuous trough eliminates glare both direct and reflected, distributes the light uniformly and presents a pleasing appearance. The interior is finished in white and acts by diffuse reflection while the exterior harmonizes with the furniture.

With such an installation as pictured in Fig. 168 the housing of the lamps, in effect, isolates readers on opposite sides of the table.

In the reading rooms of the second class of buildings are located the book stacks, and general lighting with the indirect systems is the most logical method of meeting the requirements. With the present-day high-efficiency lamps, it is perfectly advisable to supply from 6 to 8 foot-candles throughout the room. This arrangement eliminates the necessity and bother of local or table lights. The diffuse character of the illumination thus produced gives excellent lighting on the vertical surfaces of the stacks.

The Hotel.—The *lobby* is the place of contact between the hotel management and the public; parts of it are devoted to clerical

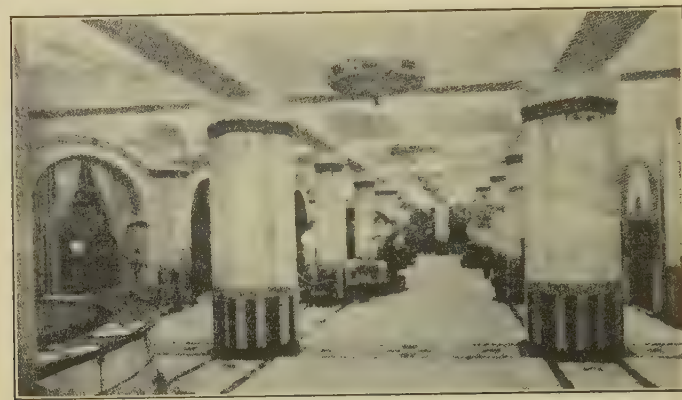


FIG. 169.—Lobby of the Hotel Traymore, Atlantic City, lighted by Mazda C lamps in totally indirect units of special design. One fixture is provided for each 19- by 22-ft. bay and contains eight 100-watt Mazda C lamps in mirrored glass reflectors. The effect produced is most pleasing; the intensity of illumination relatively high, and the unique design is in perfect harmony with the decorative treatment.

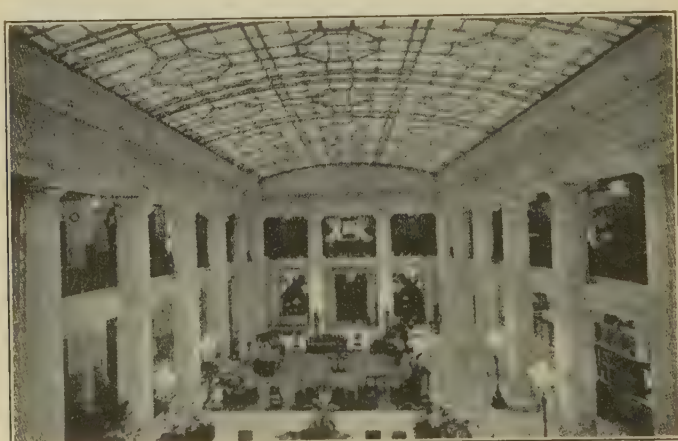


FIG. 170.—The principal lighting of the lobby of the Hotel Pennsylvania, New York, is from above the skylight. Direct lighting units with clear Mazda C lamps are placed here and distribute the light uniformly. To give a touch of color and to provide a higher intensity at certain points, floor and table lamps are employed in suitable number. In the mezzanine section and adjoining areas decorative enclosing luminaires are used. The multiple unit standards near the base of the columns are in keeping with the general classical treatment of the room.

work, other sections are used by the guests for relaxation, conversation, or reading. The size of the hotel, the architecture of

the lobby, and its furnishings will have a bearing on the illumination requirements.

In many lobbies, it is not desirable to suspend fixtures from the ceiling, due to the presence of skylights, but such rooms may be lighted with excellent results by placing direct-lighting, enameled-steel or mirrored-glass reflectors and type-C lamps above the skylight, producing an effect similar to daylight, as in Fig. 170.

Many decorative features may be added by using portable lamps, of both the floor and table types. These are also useful as well as ornamental, as the intensity of light around them is raised high enough for reading without having the entire area lighted to the same level. Brackets are also often used on walls and columns for added decoration. These are sometimes equipped with bare lamps which, against a dark background, produce a very glaring condition, even though the bulbs are frosted. This condition should be minimized by shielding the lamps with silk, parchment, or glass shades, thus reducing the contrast without losing the artistic touch. The same conditions hold where chandeliers of the candlestick type are hung from the ceiling.

Cabarets, Roof Gardens, and Grills.—Here there are excellent opportunities for producing novel and attractive lighting effects. By using a little ingenuity, the lighting may be made to fit the decorative arrangements closely.

In *roof gardens* open to the sky, floodlights have been found of considerable use. These should be placed about 15 ft. above the floor, with the center of the beam directed at the dance area. By using colored filters and stippled glass doors on the projectors the light is tinted and diffused over a wide area and by the mixing of colors a very pleasing effect is produced. Small lamps on the tables, of course, supplement the general lighting.

Colored paper or silk lanterns with low-wattage lamps hung a few feet apart on suspension wires are also appropriate in giving the garden effect. Where exposed to the weather, special glass which imitates such materials can be used. Sometimes the outdoor dining room is planned with pebbled walks winding about the tables. Here diminutive street posts with glass lantern-type enclosing globes carry out the decorative scheme. The roof garden overlooking the water many well be fitted up to resemble a vessel with typical ship lanterns, bulkhead lights, and a movable searchlight to reveal adjoining buildings.

Novelty is paramount in lighting the *cabaret*. Color is used more extensively than in almost any other class of lighting service. Unique designs of fabric lanterns, as in Fig. 171, elaborate outline, and spotlight effects are in keeping with the spirit of the room. Standard stage spot and flood lamps to illuminate the performers should be properly placed and concealed from view of the diners.

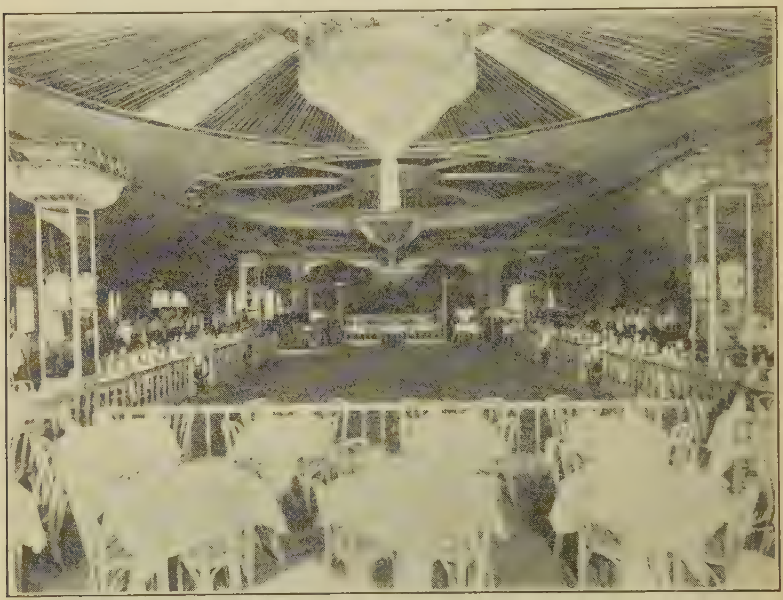


Fig. 171.—View of a prominent roof garden cabaret with a unique and effective lighting system. Three symmetrically placed ceiling luminaires with rosy silk panels concealing clear Mazda lamps are the main light sources. The tops of the mirror covered columns are extended and covered with silk forming luminous vari-colored capitals. Smaller decorative units of the same general type will be noted on the mirrors. A cove concealing colored lamps on three circuits extends completely around the edge of the room furnishing tinted, indirect illumination. At the rear will be noted an artificial cascade which is lighted by a group of "effect" machines producing moving clouds and the like. Around the perimeter of the central ring are recessed mirrored glass reflectors and clear Mazda lamps with gelatin color screens to furnish high intensity lighting on the dancing area. Several standard stage spot lamps are used to "pick up" the artists.

"Effect apparatus" finds a place in lighting imitation waterfalls or cascades and producing moving clouds on the ceiling.

Due to the low ceiling which is often encountered in the *grill*, it is sometimes impractical to use pendent luminaires. Well-shaded side-wall brackets can be installed or the ceiling recessed and the opening covered by a decorating diffusing glass plate, behind which the lamps are placed. Such lighting when supple-

mented by table lamps is particularly useful where the ceilings are dark.

A rather novel lighting system was employed in one grill which was decorated to present a rustic outdoor scene. The light from small lamps, with automatic control turning the current on and off, came through holes in the false ceiling. These very small spots of light appeared as twinkling stars against a blue background. The columns in the room were transformed into tree trunks with four protruding branches, each supporting a wrought-iron lantern with diffusing-glass panels and a 50-watt lamp within.

Restaurants and dining rooms of the utilitarian class often employ diffusing glassware in direct-lighting luminaires, sometimes

FIG. 172.—National Bank of Commerce dining room. (Bracket unit on columns.)

the semi-indirect system or indirect system. In some cases the luminaires are of the ornamental type. The efficiency of the system in general receives attention.

The installation shown in Fig. 172, in the dining room of the National Bank of Commerce, New York City, illustrates a method of dealing with large rooms having low ceilings. The bracket-type unit of the indirect system is used.

Lighting a Large Ballroom.—The Hotel Commodore houses a large hotel ballroom, 78 ft. in width and 180 ft. long, encircled by a gallery divided into fifty-six boxes with the customary promenade behind them. The decorative scheme and furnishings of the room are Italian, carried out in delicate shades of orchid, purple, white, and gold, with a base of emerald-green (see Fig. 173).

Fig. 173.—The ballroom of the Hotel Commodore, New York, is provided with a rather deep cove. In this are located mirrored-glass reflectors with 100-watt type-C lamps, directing the light towards the ceiling. The illumination is uniform, of a pleasing character and may be adapted to any scheme of decoration. In the small boxes on the balcony floor are located decorative luminaires with tinted lamps of low wattage. In the cove previously mentioned, which is deep enough to allow a man to walk, are located a number of high-current stage pockets, to which spot lamps and other apparatus are attached for use during dances, carnivals, and other events.

To flood the interior with diffused illumination and to retain the spacious appearance, the cove or cornice method was adopted, with reflector units running along two sides of the room. No reflectors are employed within 6 ft. from the corners of the room; otherwise they are symmetrically spaced about 15 in. apart. One hundred-watt type-C lamps in mirrored-glass reflectors are used. All units are wired on two circuits, with every alternate reflector on one circuit. For one set or circuit, an amber film

is placed over the mouth of the reflector, allowing for a variation or tinting of the light.

Cove lighting, although one of the oldest forms of concealed lighting, requires careful planning to insure a uniformly lighted ceiling and an absence of light and dark patches that so often unmistakably indicate the position of the individual reflector units in the cove.

To insure pleasing results in any given case, the proper size and style of reflectors should be carefully determined. The coves should be large enough to contain the suitable equipment and should be placed not too close to the ceiling, if uniform ceiling brightness is to be obtained. A means should be provided whereby the reflector equipment can be easily reached for cleaning and renewing lamps.

CHAPTER XIII

COMMERCIAL LIGHTING

The Office.—From the standpoint of utility, the problem of office lighting can be simply stated. Fundamentally, it is to provide the best illumination for sustained vision of flat surfaces in horizontal or slightly oblique planes, the angles at which papers,

Fig. 174.—Typical commercial general office lighting system using opaque X-ray reflectors and 300 watt lamps.

books, and photographs are usually examined. The perception of objects in their three dimensions, so important in the industries and in the arts, is here relatively unimportant. On the other hand, experience has shown that in offices and drafting rooms, perhaps more than in any other locations, an ample intensity of soft well-diffused light must be provided in order that discomfort may be avoided and that the eyes may not become excessively fatigued by close application for long periods of time. There should be no extreme contrast in the brightness of objects within the field of view; shadows should be subdued, if not entirely avoided; the lighting system should be designed to permit

flexibility in the arrangement of office furniture; it should be easy of maintenance and satisfactory in appearance.

Local lighting is objectionable, as there is a great liability of glaring reflections from desk surfaces and glazed paper; the clerk loses time in shifting the light about; the breakage of lamps is increased; and there is often marked contrast between the brightly lighted desk area and the rest of the room. General illumination is, therefore, practically standard. Overhead units alone are used —lighting the whole room uniformly. The lamps are so placed that they are well out of the ordinary angle of view, equipped with diffusing glassware, and arranged in such a manner that dense shadows are avoided. This scheme also permits the use of larger lamps, which, as a general thing, are more efficient than the smaller sizes. Since fewer outlets are required, the cost of wiring is reduced. A great deal of careful investigation has proved that general illumination is a real economy, all things considered, in comparison with local lighting.

Good office lighting provides a high intensity of illumination. For satisfactory lighting, it is desirable to have the illumination on a given desk or table received from several sources. This method introduces what might be termed "cross-lighting" and tends to eliminate shadows.

In planning the location of outlets, it is desirable to space these symmetrically with regard to the bays or columns. Standard construction is tending toward 20-ft. bays in office buildings and for the ordinary heights of ceiling four outlets per bay are to be preferred. If the bays run larger than this, it is often advisable to increase the number of outlets to six, as future demands may necessitate the dividing of the large space into two or more small offices. The six-outlets-per-bay arrangement often meets these conditions without necessitating any additional wiring. In some cases additional outlets are provided, but are not fitted with fixtures (the outlet box merely being covered with a neat cap) to make provisions for the future and to avoid the necessity of opening the ceiling for rewiring.

Where an unsymmetrical arrangement of outlets is necessary they should be located relatively nearer the windows than the inside wall, for the predominating light will then come from the same direction as daylight.

In wiring large offices, lamps should be controlled in rows parallel to the windows rather than in groups perpendicular to the

windows. By this arrangement the center of a wide room, where artificial light is first demanded, can be lighted before the section nearer the window.

It is very rare that an office can be lighted satisfactorily by one outlet, and even a small clerical office should have from two to four outlets, depending on its size.

For private offices, it is often very satisfactory to provide a relatively low intensity of general illumination by some decorative central unit and use a localized light of satisfactory design for the desk. This should be located in such a manner as to prevent glaring, annoying reflections. Where glass-top desks are used, particular attention must be paid to the type of lighting fixtures, to avoid reflections.

Drafting Room.—Although the lighting requirements of the drafting room are somewhat exacting, they may be readily met if due care be taken in the selection and location of lighting units. The ideal condition is an even distribution of well-diffused light of a high intensity. Shadows must be minimized, as they make it difficult to follow the fine lines when working close to the T-square or triangle.

The discussion of office lighting applies to drafting room lighting. The requirements are even more exacting, as the work is particular and must be accurate. Semi-indirect systems where dense glass is employed, or totally indirect systems, are probably the best suited.

Direct general illumination of a high intensity, using rather close-spaced semi-enclosing units, is also used where the ceilings are so dark as to preclude the use of indirect systems. The units should be located with reference to the drawing tables and so arranged that the maximum light will come from the proper direction. Lamps must be hung well out of the angle of vision and every effort made to avoid glare.

In both the direct and semi-indirect systems of illumination due note must be taken of the usual arrangement of boards relative to the windows, locating the lamps so that, as far as possible, the direction of predominant light is the same as that of daylight.

Store Lighting.—The value of the psychological influence and advertising effect of good store light cannot be overestimated. Many systems of interior lighting may be used. The lamps should be properly placed and so equipped that they are not

glaring. The installation should be artistic and so arranged as to give a pleasing appearance. The intensity of illumination on the goods should be ample, depending on the color and character of the goods displayed. General lighting is universally used. Lamps are arranged symmetrically with regard to the bays or pillars, and the whole floor uniformly lighted. It is not neces-

FIG. 175.—The ceiling height of large stores is usually such that one outlet per bay permits satisfactory illumination.

sary to take into account the position of the counters when spacing the lamps, for a sufficiently high intensity is provided everywhere to make it possible to examine the goods on display carefully. If the rules for spacing outlets are observed, there need be no fear of objectionable shadows in any part of the building.

As a general rule, it is never advisable that the distance between lamps be greater than the ceiling height. In many stores the ceiling of the first floor is much higher than those of the upper floors, and while one large unit per bay may be satisfac-

tory on the main floor the others may require at least two outlets per bay.

Using a few outlets keeps the cost of wiring at a minimum and permits the economical use of the larger, more efficient lamps. On the other hand, with the smaller lamps the light at any one point is received from a greater number of sources; hence the possibility of shadows is lessened, and the failure of one unit does not put a section in darkness. It is desirable to have an even distribution of light at the counter level, in order that there may be no spots in shadow. This condition can be fulfilled by hanging the lamps at suitable heights. In general, the following rule applies:

It is always desirable to place lamps as high as possible to keep the light sources from the line of vision, but this rule should not be carried to such an extreme that a distorted appearance results.

An attempt has been made below to classify the various types of luminaires suitable for use in the store, in the general order of their effectiveness in certain directions. This summary is based on the average high-grade store finish of pure white.

Maximum light on the counters for a given amount of power:
- Efficient prismatic bowl reflectors.
- Opal bowl reflectors.
- Opalescent enclosing globes (quite dependent on the kind of glass used).
- Semi-indirect.
- Totally indirect.

Diffusion or softness of illumination:
- Totally indirect.
- Semi-indirect.
- Opalescent enclosing globes.
- Opalescent bowl reflectors.
- Prismatic units.

Bright-appearing store:
- Opalescent enclosing globes.
- Semi-indirect.
- Opalescent bowl reflectors.
- Prismatic units.
- Totally indirect.

Except where decoration is of major importance, *e.g.*, the ladies' rest room, simple designs of fixtures serve best. Plain, well-finished metal in the form of single stems or pipes, or a

canopy and drop chain, can be used to support any of the forms of direct-lighting units.

The semi-indirect bowls are carried by three or four neat metal chains attached to the supporting canopy, various forms of hooks being used to attach the glassware to the chain. In general, the lamp hangs pendent; sometimes a combination of a short length of pipe or reinforced cord with projecting arms is used in place of chain suspension.

The indirect equipments are usually supplied complete with chain or pipe support, finished to match the fixture.

Fig. 176.—The soft, even illumination obtained with these semi-indirect luminaires is not appreciably affected by the silk shades which harmonize with and add greatly to the appearance of this ladies' apparel shop.

Window lighting is an important part of store lighting. The display should be so lighted that it will not only attract, but will compel, attention. The lamps should never be in view, but should be hidden with drapery or other valance. Special reflectors to direct the light onto the display are, of course, necessary. The intensity of illumination will depend on the color of the goods, the importance of the location of the store, and whether there is a surrounding high intensity from street lights, signs, etc. A high intensity of illumination in the window will make it stand out more prominently.

Illustrations of show-window lighting are shown in Figs. 177 and 178.

In general, the light must come from in front of the goods in order to avoid bad shadows. Shadows are necessary, but they should not be too sharply defined. There should be no difficulty in distinguishing objects in shadow, and the edge of the object should not be confused with the edge of the shadow. The so-called shadowless windows are unsatisfactory, since the sense of size, proportion, distance, and texture are either lost or so badly distorted as to repel observers rather than attract them.

Lighting units should be placed in the upper front part of the window. In order to introduce the certain element of diffusion mentioned above, a number of small lamps are preferable to one large unit giving the same amount of light. There may be exceptions to this rule.

Except under special conditions (where the display is practically on the floor of the window) lamps should never be placed in the middle of the show-window ceiling, for this arrangement causes the front of the goods displayed in the foreground to be in shadow. Also lamps so placed cannot be effectively concealed.

A lamp should never be placed directly outside of the window. Some persons think this necessary to attract attention, but the glare from a high-candle-power light source for this purpose is very bad. A light outside the window causes the sidewalk to be brilliantly lighted, which is not the best condition, for a window should stand out by contrast. Lamps outside of a window do not light the goods effectively.

The window background should be arranged to suit the dress. It should be chosen to avoid specular reflection. A mirrored backing is particularly undesirable as it shows the reflection of the show windows on the opposite side of the street as well as the lighting units of the window itself. Many windows have glass above the paneled woodwork in the rear for the purpose of allowing daylight to enter the front portion of the store. To avoid reflections from this glass, shades that harmonize with the background should be provided to cover it at night.

Some of the windows of recent construction have a feature which is quite desirable from the lighting standpoint. They employ a light-colored background with matt or dull finish. The light background makes the window appear especially prominent, while the dull surface prevents annoying reflections of the lamps.

In lighting an island window, there are exacting conditions not found in windows viewed from only one direction. As the

material on display is seen from all sides, it is necessary so to illuminate it that it will appear well, regardless of the angle from which it is viewed. Any light sources in the field of vision will detract from the display, as they are a source of glare. In some island windows the ceiling is dome-shaped rather than flat, and a cove is provided on all four sides of the window at the lower edge of the dome. Around this cove are lamps located in suit-

FIG. 177.—Arcade type show window,. Provision is made for colored screens over the openings of the reflectors at the ceiling.

able mirrored reflectors, so placed that the light is directed to the dome of flat white finish. With this arrangement no lamps or reflectors are visible and the method of illumination is, of course, totally indirect. In one satisfactory installation, approximately 15 watts per square foot of floor area was employed.

Spotlights.—The effect of a concentrated beam of definite shape of rather high intensity is novel in the show window and has a distinct value. An inexpensive suspension-type spotlight is on the market. This consists of a cylindrical housing, socket, focusing device, and lens for obtaining the spot. Round-bulb concentrated-filament 500-watt lamps should be used in this device. Color screens are placed across the lens opening and changed as occasion requires.

The *daylight* lamp has become another valuable medium in the hands of the display manager. An installation of daylight lamps makes the window distinctive and prominent. A window so lighted is very striking and the goods are shown in practically their daylight value. It is not expected that the daylight

Fig. 178.—Night view of a show window utilizing the most modern lighting effects. Three brilliant red gowns are displayed against a green and black velvet background. General lighting provided by 150-watt Mazda C lamps in individual angle reflectors on one-foot centers. Half of the units are equipped with amber color screens. A spot lamp directs a strong beam of unmodified light on the artificial (silver cloth) plant in the background. The general illumination of a light yellow tone emphasizes the color of the gowns in a most striking manner. It is interesting to note that the floor and structural elements are light in color and with a dull finish. All lighting equipment is hidden from view by the draperies.

lamp will effectually supersede standard lamps for window lighting, yet certain displays are shown to their best advantage under this kind of light. Under the light of the daylight lamp, linens and white goods appear pure white rather than slightly yellowish; men's clothing, particularly if blue or black, shows up splendidly;

furs, jewelry, shoes, neckties, and the like are most satisfactorily displayed under the daylight lamp. Along with the other colored lamps a set of these approximate daylight lamps for a couple of sections of the show window should be available, and when such displays as those mentioned are set up, these lamps should be installed to obtain the best effect. With colored lighting it is possible to vary the equipment as occasion demands, avoiding monotony and obtaining the best advertising value.

Color window lighting was brought to the general attention of the electrical industry in 1919 at the convention of the National Electric Light Association at Atlantic City. Color effects were obtained by the use of gelatin screens on standard show-window reflectors. Theatrical spotlights with colored screens were also used for special effects.

This particular display consisted of an exhibit of wicker furniture, with the window arranged somewhat like a summer porch. The combination of lighting which gave the most pleasing results consisted of green general illumination, a low intensity of unmodified footlighting, portable table and floor lamps of low wattage, and two overhead spotlights furnished with purple and orange screens respectively, directing beams of light at the base of the portable lamps.

Another early illustration occurred in the window of a New York City store. The solitary exhibit in a particular section of the window consisted of a gigantic peacock with tail outspread. The lighting of this was accomplished by a relatively low intensity of blue illumination from footlights, the regular lighting turned off. Overhead, at one corner of the window, was located a standard incandescent stage spotlight, so focused that it produced a circle of illumination approximately 2 ft. in diameter on the tail of the bird. The combination was particularly impressive and attracted much attention. Still another example is shown in Fig. 30 and its details there cited.

Colored lighting also has a field in the lighting of pictures in art galleries, art exhibits, etc.

Stage Lighting.—Stage lighting, in general, exemplifies many of the principles of correct illumination—for instance, a brilliant glaring light source is never seen on the stage. Footlights, border lights, floods, etc. are invisible to the audience. The stage manager knows that unshielded lamps distract the attention, fatigue, and annoy. When he finds it necessary to have a chande-

lier, portable lamp, or bracket fixture as part of the setting, he is clever enough to provide merely enough light in this to render it luminous and does not depend on it for any actual illumination of the scene. A single glaring light will destroy the effect of the most pleasing set. In order that the picture may appear natural, the mechanism of the lighting is entirely concealed from view.

At best, stage lighting is a "cut-and-try" proposition, and its solution cannot be had by following any set rules. Experience in the handling of light and lighting apparatus is an essential as in

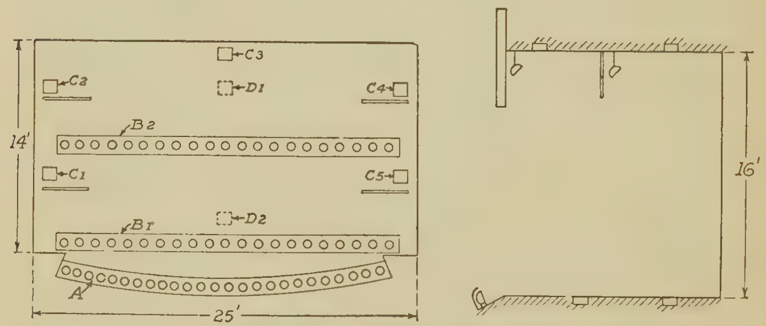


FIG. 179.—Plan and elevation of medium size stage in hall or assembly room. A, Footlights, outlets on 9-in. centers. Mirrored glass or aluminum finish steel reflectors—75-watt Mazda C lamps—gelatin color screens—three circuits (1-2-3). B_1-B_2, border lights—outlets on 12-in. centers. Mirrored glass or steel angle reflectors—100-watt Mazda C lamps, glass color caps—three circuits in each border (4-5-6-7-8 and 9). C_1 to C_5, floor or side wall stage pockets or convenience outlets of 15-ampere capacity each. D_1-D_2 convenience outlets in borders or ceiling of 10-ampere capacity. Switchboard circuits as follows: 1-2 and 3, footlights; 7-8 and 9, border lights B_2; 15 and 16, ceiling outlets D_1-D_2; 4-5 and 6, border lights, B_1; 10 to 14, stage pockets C_1 to C_5; 17, orchestra lights. Dimmer control as follows: Circuits 1, 4 and 7 combined. Circuits 2, 5 and 8 combined. Circuits 3, 6 and 9 combined. Auxiliary apparatus desirable: Olivette type bunch lights for 1,000-watt Mazda C lamps with individual dimmers on stand and gelatin collar screens—2. Suspension type spot lamps for 500- or 1,000-watt concentrated filament Mazda C lamps—2. Baby spot lamp for 250- or 400-watt concentrated filament Mazda C lamps—4. Long throw spot lamp in balcony—1.

no other field. One must have the light just where it is wanted, just when it is wanted. For an artistic production, the distribution must be accurately controlled, and skilful manipulation of dimming devices, following every line of the play or movement, is necessary.

Standard equipment probably will not always fill the bill, and in many instances it is necessary to construct special apparatus. To prevent light reaching certain parts of the stage, "louvers" or "spill shields" are essential. Obviously, these have

to meet particular conditions and must be made "on the job." Where reflecting devices are in use, it may be desirable to cover portions of these with black paint to secure a modification in distribution.

In planning stage lighting, the general principles of the action of colored light on colored objects should be kept in mind. By the application of these principles one set can be used for two or more scenes by manipulation of lights, avoiding the necessity for changing scenery. For many types of productions very little painted scenery is necessary. Colored lights can be used to obtain all the effects desired. It will be found that much more artistic and subtle gradations of tint are possible than when the attempt is made to produce these by the brush. Ingenuity, appreciation of the fundamental principles, and experimentation are necessary.

For certain types of productions, one should reproduce as nearly as possible lighting conditions as they exist in nature, and at the same time enable the audience to see clearly the actors and setting. On the other hand, many of the stagings of the present day are of what might be termed an imaginary type, and it is even possible to improve on natural lighting by skilfully applied artificial illumination. No doubt some of the most pleasing results are secured when bizarre effects are attempted and combinations of colors used which do not exist in nature. In doing this none of the fundamental principles are being violated but advantage is merely being taken of the available media for expression and something interesting, striking, and pleasing to the eye produced.

To accomplish these things, it is necessary to have available light of various colors from many different directions and facilities for changing the direction of light, as well as the quantity or intensity.

Stage-lighting devices may be divided in two main groups, those for providing general illumination and those for providing localized lighting. In the first group fall the foot, strip, proscenium, and border lights; in the second, the bunch and spotlights and effect machines or sciopticons.

The *footlights* direct a rather strong light from below, which intensifies the facial expression and assists to a great degree in holding the attention of the audience. Such lighting tends to reverse natural shadows, however, and, while still an important

factor, is much more subdued than in the early days of the art. Some of the most artistic productions of recent years have been well lighted without the use of footlights. It is doubtful whether this practice should be universally applied and it is always well to provide suitable footlights for use when necessary.

The modern type of footlights employs type-C lamps with individual reflectors and gelatin color screens.

The *border lights* furnish general illumination from a natural direction. They are therefore a necessary part of the stage

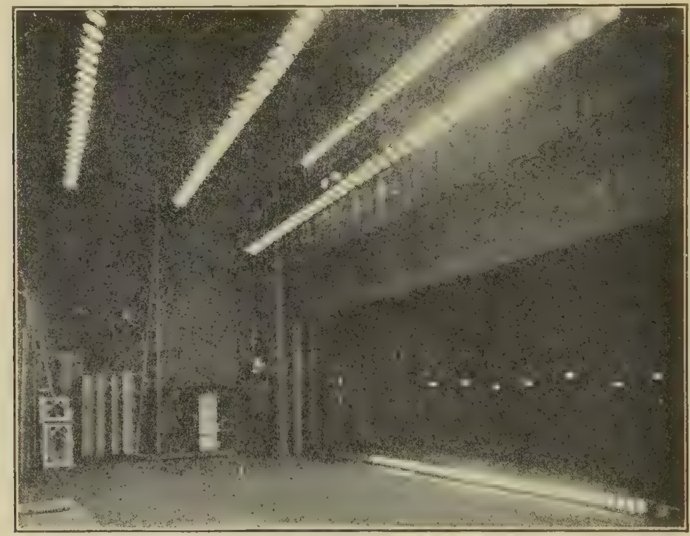


Fig. 180.—Individual aluminum finish steel angle reflectors with 100-watt Mazda C lamps are used as border units on this stage. The color screens have been removed. Three circuits are provided in the borders and four in the concert border. Footlights are similar in character but more closely spaced.

equipment. The newer forms of border lights employ high-efficiency lamps, individual reflectors, and color screens similar to the footlights.

Illustrations of footlight and border-light practice are shown in Figs. 179 and 180. *Spotlights* and *flood-lighting units* are often used when it is desired to draw the attention of the audience to some special part of the scene or to light a given area to a higher intensity.

Color effects and the production of colored light are discussed in Chap. III.

CHAPTER XIV

INDUSTRIAL LIGHTING

Good illumination, both natural and artificial, in the industries and bright and cheerful surroundings produce the following results:

1. Greater accuracy in workmanship.
2. Increased production for the same labor cost.
3. Decreased spoilage of product.
4. Less eye strain.
5. Reduction of accidents.
6. Better working and living conditions.
7. Greater contentment of the workman.
8. Better order, cleanliness, and neatness in the plant.
9. Easier supervision of the employees.

Sufficient illumination should be provided for each workman, irrespective of his position in the working space. The luminaires should be of such a type as to minimize glare, properly located, and of sufficient number to eliminate objectionable shadows.

Many industries, owing to the diversified requirements, call for a wide range of intensities. For instance, in the shipping room of a clothing factory, 4 foot-candles may prove satisfactory, while 20 to 50 foot-candles at the needle point may be found necessary.

The Lighting System.—If the required intensity can be economically produced by the system of general illumination, such a system is recommended. If, on the other hand, the economic limit is passed before the intensity has reached the necessary value, a localized general system should be employed, with recourse to a combined local and general system, when the limit has been reached with the localized general system. Hence, it will be seen that, with the diversified requirements, the theoretical proper intensity of illumination will vary for each factory and for each class of work being carried on, and consequently it will be difficult to set definite limits. Experimentation has proved, however, that certain intensities which come well within the

economic limits of good lighting give beneficial results from every viewpoint, and, therefore, recommendations should be based upon these values.

Where individual lamps are absolutely necessary because of the nature of the work they should be placed close to the work and provided with suitable opaque reflectors.

Illumination and Production.—The relation of quantity of light to production has been investigated in a number of industrial plants with the following general results:

Average old intensity, foot-candles	2.00
Average new intensity, foot-candles	11.00
Increased production, per cent	15.5
Increased cost, per cent of payroll	2.4

Similar relations between intensity of illumination and speed resulted from card-sorting tests, which involve both speed and

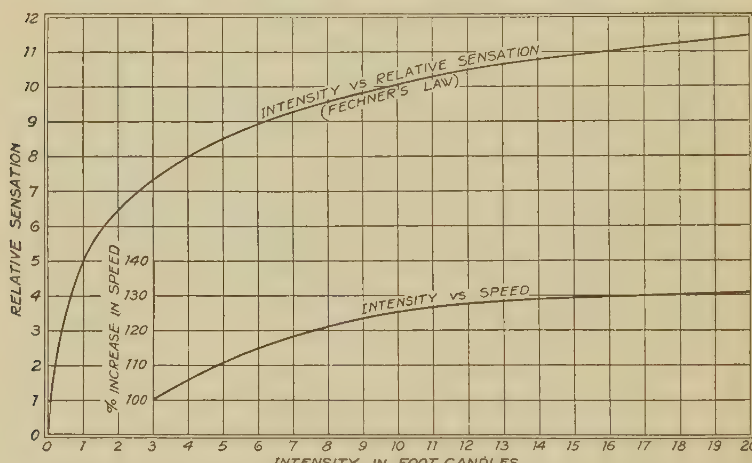


FIG. 181.—Curves showing the general similarity in shape between Fechner's law and the results of several "card sorting" tests.

accuracy. A composite curve from the results of several of these tests is shown in Fig. 181. It will be noted that this is of the same general shape as the curve for Fechner's law.

Spoilage.—That correct and adequate illumination has a marked effect on the question of spoilage is recognized. The mechanic can more easily and accurately read his blue prints, micrometers, and gages under proper lighting. When working to exact specifications, the reading of a micrometer a thousandth

off may mean the difference between a "first" and a "second." The carpenter, the weaver—in fact, anyone—will find it easier to work correctly under high-level lighting.

Safety.—The question of safety cannot be too greatly emphasized. Approximately one death in twelve is due to accident causes.

F. E. Morris, Chief Secretary of the National Safety Council, Chicago, said that during the 19 months the United States was in the war, 56,000 American soldiers were killed in Europe. During the same period 226,000 men, women, and children were accidentally killed in the United States.

Records of insurance companies suggest that some 25 per cent of the industrial accidents might have been avoided, if adequate illumination had been provided.

Reflector Equipment.—It is obvious that, to obtain effective illumination, lamps must be equipped with suitable reflectors to protect the eye from the bright filament and to direct the light on the work. It is also necessary to diffuse the direct light from the lamp and thus soften shadows. With open reflectors, therefore, the bowl-enameled lamp is employed.

Present practice is tending toward the universal adoption of the RLM standard dome reflector and bowl-enameled lamp as the lighting unit for the great majority of industrial processes. This reflector was designed by representatives of the leading manufacturers, especially for service with type-C lamps. It gives a desirable distribution of light for most purposes and is efficient. It is built to certain specifications as to light output, gage of metal used, quality of enamel, angle of cut-off, etc., and while in the process of manufacture is subject to periodic inspection by representatives of a prominent testing laboratory, so that the purchaser can be assured of a high quality. The porcelain enamel finish is particularly advantageous, for it can be easily cleaned and its luster is not destroyed by scrubbing. It is not affected by moisture or acid fumes, and after cleaning it returns to practically initial efficiency.

A new type of reflecting equipment, known as the Glassteel diffuser (Fig. 182), bids fair to be useful for high-grade work where diffusion is especially desired. Its efficiency, using clear lamps, is approximately the same as the RLM reflector with bowl-enameled lamps. Its important feature is excellent diffusion and minimum glare. It consists of an enameled-steel reflector,

similar to the RLM standard, but of larger diameter, and a specially designed opal globe. Small openings in the steel reflector permit about 10 per cent of the light to go directly to the ceiling. Several sizes of lamps can be used advantageously with the same size of reflector, often permitting the changing of the lighting to accommodate a rearrangement of processes, simply by relamping. This equipment is best suited to the higher grades of lighting.

The deep-bowl metal reflector gives a lower cut-off. This very fact, however, tends to reduce the amount of light on vertical

Fig. 182.—Print shop using 200 watt lamps in Glassteel diffusers. Extra lamps are placed over presses, imposing stones, etc.

surfaces and, although there may be excellent illumination on the working plane, a room often appears dull and cheerless when bowl reflectors are employed. Light-colored surroundings reflecting and diffusing the light tend to overcome this difficulty. The deep-bowl reflector is especially serviceable in local lighting with low-hung lamps.

Angle metal reflectors are used where especially high illumination is required on vertical surfaces and where lighting units must be located on the side walls. They are frequently placed below the crane track and should generally be supplemented by overhead units.

A number of types of specially designed metal reflector equipments for industrial lighting provide additional means of diffusing the light. Sometimes a polished metal cap is placed over the lower half of the lamp bulb to cut off the direct light from the lamp. In other instances diffusion is accomplished by opal-glass diffusing caps, and some devices employ a shield of metal on a level with the filament. If the reflector itself is properly designed, these additional accessories tend to eliminate sharp shadows and annoying reflections from the work, at a reduction in total output of light and a somewhat higher cost of equipment.

Prismatic, mirrored, and dense opal deep-bowl glass reflectors are also used. These can be very efficient and give suitable distributions of light. The translucent types produce a bright, cheerful room. While it is evident that the likelihood of breakage is much greater than where metal reflectors are employed, the hazard is not so great as often assumed.

Enclosing or semi-enclosing units of opalescent or diffusing glass find quite an extensive application. They produce excellent diffusion with slight sacrifice in efficiency. A room so lighted is generally agreeable and attractive.

Whatever system of illumination is chosen, it is good practice to provide light-colored upper walls and ceilings and refinish these at frequent intervals. Light which would otherwise be wasted is thereby conserved.

Background.—The effect of the background is frequently neglected in planning a lighting installation. For close inspection or prolonged visual effort the background should be darker than the object worked upon. A proper degree of brightness contrast is necessary for comfortable vision.

Without brightness contrast a flat field is present which renders it extremely difficult for the eyes to focus, either voluntarily when working, or involuntarily when resting. A common method of breaking up the field of view and preventing this flatness is to paint a dark-green dado about 4 to 8 ft. high on the walls of the room.

Factory interiors are usually divided by columns into bays, or rectangles, of uniform size, as shown in Fig. 183. Such bays afford convenient starting points in determining the location of the lighting units. It is desirable that the lighting units be symmetrically spaced throughout the whole of an interior. This will result if the units are properly spaced in each bay.

Furthermore, a correct lighting design presented in terms of individual bays can be readily extended throughout a plant of only a few or of many bays.

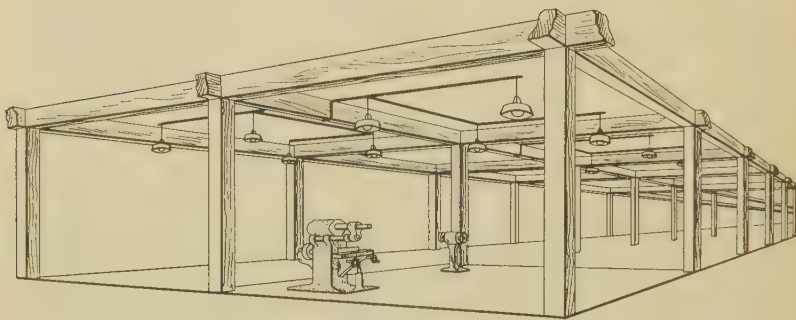


Fig. 183.—An industrial interior can usually be divided into sections, or bays, by which the lighting units can be located in the design of a modern lighting system. Sometimes, where no structural features suggest a natural division into bays, it will be necessary to sketch a floor plan and to draw in imaginary bays of uniform size, the size depending upon the grouping of machines, benches, etc. These bays should be chosen as nearly square as is practicable. In the interior shown, beams divide the interior into 20 × 20 ft. bays; 4 units are symmetrically spaced in each bay.

Many times in interiors where there are no columns the arrangement of beams on the ceiling, or trusses, will suggest a natural

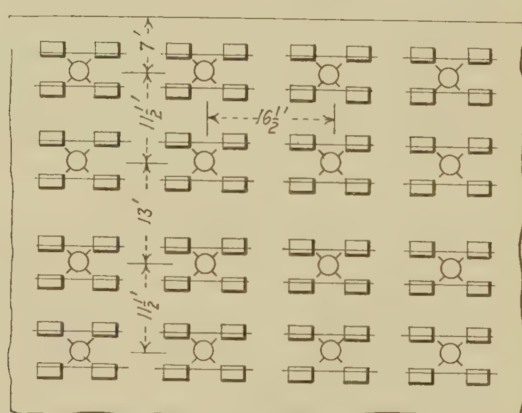


Fig. 184.—Group lighting of weave room of cotton mill.

division into bays. Attention is called to the fact that large bays can frequently be split up into a number of smaller bays corresponding in size to some one of the common sizes.

It is frequently the case that the arrangement on the floor of large machines or of groups of smaller machines, as, for example, in textile plants, will permit what is known as "group" lighting, that is, the location of the lighting units with respect to the

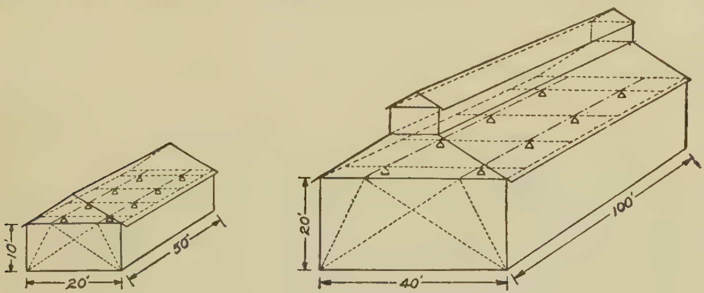


FIG. 185.—Illustration of effective angle.

machines rather than the structural features of the interior. An example of group lighting is shown in Fig. 184.

Contrary to the general belief, the absolute height in feet at which units are mounted has in itself no influence upon the percentage of light utilized, so long as the same proportions are maintained. For example, if there are two buildings,

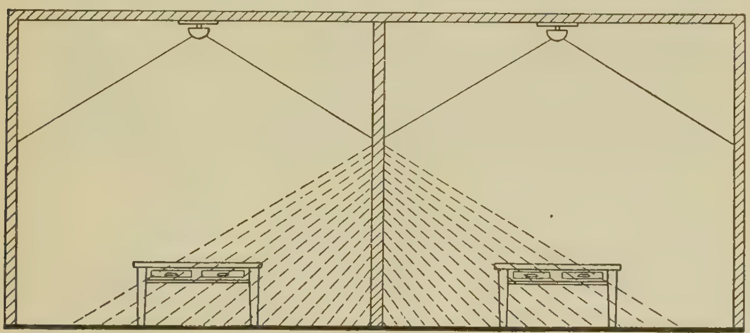


FIG. 186.—The coefficient of utilization is dependent upon room proportions. The light striking the partition is largely lost.

one 20 by 50 ft. and 10 ft. in height, and the other 40 by 100 ft. and 20 ft. in height, it is clear from Fig. 185 that the effective angle, and hence the efficiencies of the lighting systems in the two buildings, will be the same. If the small building is illuminated by eight 100-watt lamps on 10-ft. centers and the large building by the same number of 400-watt lamps on 20-ft. centers,

the average intensity of illumination will be the same[1] and its distribution will be similar. On the other hand, the *proportions* of a given building or room have an important bearing upon the percentage of light utilized. This is shown in Fig. 186, where much of the light is absorbed by the walls in a small room, whereas in a large room these light rays would be available on the work plane.

Bench Work.—Many processes are carried on at the benches, such as assembling small parts, soldering, sorting, filing, and

Fig. 187.—Night view of well lighted benches and assembly area. 150-watt Mazda C lamps in glass top dome reflectors are spaced on 8-foot centers. Units for general illumination are close to the 12-foot ceiling while those over the benches are eight feet high. Outlets are located between vises. The even distribution and the ease with which every detail is clearly discernible is apparent.

general vise work. It is apparent that different intensities of illumination will be required.

Benches fall in two general groups, single benches 2 or 3 ft. wide along the walls, and single or double benches away from the walls.

Single benches along the walls should be lighted by a row of lamps about 6 in. in from the forward edge of the bench spaced on 6- to 10-ft. centers with from 40- to 100-watt bowl-frosted or bowl-enameled lamps in deep-bowl or standard dome reflectors.

[1] Neglecting the difference in the efficiency of the units.

The size of lamp will depend on the fineness of the work and the spacing on the location of the vises or working points. It is desirable to locate units between vises rather than directly above them, for with this arrangement light is received from the two sides and the operator is less likely to cast a shadow on the work. The units for bench lighting should be hung about 5 ft. above the bench.

Where general illumination is used for the shop with outlets symmetrically spaced, as, for example, four outlets on 10-ft. centers per 20-ft. bay, it is often feasible to move the first row of outlets 2 or 3 ft. nearer the wall than would be done for a strictly symmetrical arrangement and thus obtain satisfactory bench lighting with but little sacrifice of general illumination and a minimum number of outlets. Such a scheme is followed in the plant illustrated in Fig. 187, where outlets are on 8-ft. centers.

For benches away from the wall, general illumination is quite satisfactory, provided fairly close spacing of outlets (not over 10- or 12-ft. centers for ordinary conditions) is adhered to. Where the ceiling is very low or the work exacting, localized general illumination (see Figs. 184, 187, 188) with the units arranged as suggested for benches along the wall is sometimes necessary. Again, where minute parts are handled, as in the watch factory, or for very close inspection work, local lighting offers the most economical means of providing the high intensity (50 foot-candles and upwards) necessary; this lighting should, of course, be supplemented by general illumination.

The intensity for bench lighting depends on the type of work carried on and ranges from about 6 foot-candles for soldering to 20 foot-candles for accurate fitting of machine parts.

It is almost always desirable to avoid specular or image reflections of the light sources from polished surfaces, yet there are a few exceptional cases where such reflections are necessary if the work is to be carried on satisfactorily by artificial light. A piece of polished metal cannot be illuminated so that imperfections will show up by diffuse reflection, as they would in some cloth, for example. When inspecting glossy surfaces by natural light, the inspector holds the object so that the sky is reflected from its surface, and thus detects irregularities. With artificial light it is necessary to duplicate this condition by having a relatively large diffusing source so placed that the inspector can view the reflection of this in the surface of the metal.

Machine Tool Work.—There are a few processes, including deep boring, punching and pressing of large blanks, lathe work on minute parts, such as watch mechanisms and the like, which require local lamps. With these few exceptions, machine tool work can be carried on most effectively with the artificial lighting taking the form of overhead units. This statement is borne out by numerous satisfactory installations in constant use. Many mechanics will argue otherwise, thinking they cannot work unless there is a drop lamp directly over the tool, but this is largely a question of psychology. After a new system has

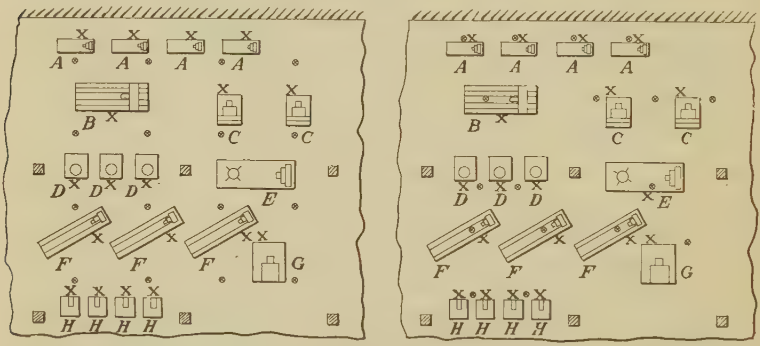


Fig. 188.—Typical section of a machine shop. At the left is shown the arrangement of outlets for symmetrical general illumination; at the right is shown arrangement of outlets for localized general lighting. A—lathe (engine). B—large planer. C—shaper. D—drill press. E—lathe (turret). F—automatic screw machine. G—universal miller. H—emery wheel and buffer. O—lighting outlet. X—position of operator.

replaced the old, everyone is usually enthusiastic in his praises, after becoming accustomed to the change.

Where the ceiling is low, in order that the predominant light may come from the proper direction, it is most generally advisable to use localized general lighting, which is an intermediate practice between general and local lighting. In Fig. 188 is shown the difference in arrangement between a general and a localized general-lighting layout. In the symmetrical arrangement, an analysis shows that many of the units are quite ineffective. For example, two are located directly behind the shapers, in which position they would be of little use. The lighting of the lathes along the wall would be from the wrong direction; the headstock would cast a shadow on the work. A similar analysis might be carried out for the entire hypothetical arrangement. In the other half of the illustration lighting units are arranged so that the

correct direction of light results, the position of each machine being taken into consideration.

If the number of units in the four bays pictured is tallied, the general lighting system would show sixteen and the localized general seventeen. With such arrangement, each machine receives the kind of lighting it requires. All the advantages of general lighting are obtained and the disadvantages of local lighting eliminated. No attempt should be made to place the outlets for a machine shop with a relatively low ceiling without taking into consideration the localization of the individual machines.

The following general rules indicate the desirable direction of light for the different types of machines:

Lathes: From above to the right of the chuck, very slightly forward.

Millers and shapers: From above, in front, and preferably both sides.

Planers: Large machines above center of bed when at end of cutting stroke; on planers where it is advisable to supply only moderate general illumination, a small lamp with reflector may often be mounted near the tool.

Small machines: See shapers.

Drill presses: From above, in front, unless overhanging parts prevent, then slightly from the side.

Buffers, grinding wheels, etc.: Above the wheel, slightly forward.

Saws: In line with the saw, slightly forward.

Machine Sewing.—The requirements in a sewing room are diversified. The type of machines, the quality of the work being done, the color of the goods, the color of walls and ceilings, and the liability to accumulate dust must all be considered in deciding upon and laying out installations.

The two main positions at which light is required on the sewing table are, first, at the side of the machine where the goods lie prior to being sewed together; and, second, at the needle point. For the former a medium intensity of illumination will suffice. It is obvious, of course, that a greater amount of illumination will be necessary when working on dark goods rather than on light goods. Owing to the unsymmetrical arrangement of the goods many shadows are produced, hence a well-diffused, properly distributed illumination is essential if the vision of the operator is to be quick

and sure. For this work a system of general illumination will be found applicable.

The light at the needle point, however, must be of a high intensity. Seldom will an illumination below 8 foot-candles in intensity prove satisfactory, and in many cases it is advisable to have this intensity as high as 50 foot-candles. Where the conditions of work are of an ordinary nature, 8 to 12 foot-candles of illumination can be produced satisfactorily by an overhead system of general or localized general illumination. Where extremely high intensities are necessary, it is advisable to furnish the high inetnsity of illumination at the needle point by a local lamp (Fig. 189), while a somewhat lower intensity is supplied throughout the remainder of the room by a system of general illumination.

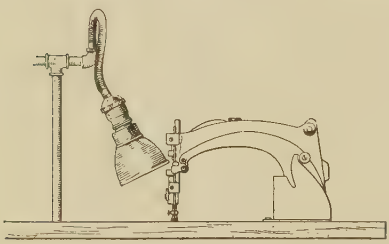


Fig. 189.—Fifteen-watt lamps in the local lighting unit shown above will produce 40 foot-candles at the needle.

Hand Sewing.—This is usually very fine work and requires good illumination. The natural posture for the operator to assume is, while seated, to take the work on her knee. Hence, it is extremely important that no objectionable shadows be cast upon the work. It is also obvious that the predominating light should come from slightly in front of the operator, preferably from the left.

Satisfactory results can be obtained from general illumination over the sewing table, units being hung from 5 to 6 ft. above the surface of the table and spaced about 8 ft. apart; 100-, 150-, or 200-watt bowl-enameled lamps in standard dome reflectors should be used, the size of unit, of course, depending upon the class of work. This arrangement will insure good diffusion, objectionable shadows will be reduced to a satisfactory minimum, and the operators will not be handicapped by having a local light constantly in their way.

Inspection and Folding.—Inspection is, perhaps, the operation which makes the most exacting demands upon illumination. Inspectors not only examine the work, but detect stains, errors in colors, faults in the goods, etc. They are called upon to do this with reasonable speed and great accuracy. Therefore a light should be employed which will bring out all these defects in as

pronounced a manner as possible. In many factories as much of the inspection as is possible is done entirely by daylight, as it is found that the color quality of daylight is a distinct asset in matching and detecting imperfections.

It is obvious that satisfactory artificial illumination for this class of work should simulate daylight in color value. Where extreme accuracy of color matching is important, the most accurate type of color-matching unit should be used. In a large number of cases, however, the daylight lamp, by supplying a quality of illumination which permits discrimination of color and discernment of imperfections in cloth, will meet the requirements.

The method of installing these units, of course, varies considerably with the class of work and the methods of the management. In underwear factories, for instance, some managers believe that it is efficient for the inspectors to fold the garment as it is inspected, others believe strongly in the advisability of an inspection department separate from the folding department, while others believe in combining both departments, that is, placing inspectors and folders side by side—two folders to each inspector. For the first two methods mentioned a system of general illumination would be preferable and it would be desirable to have this illumination of a daylight color value. In the third case, however, the tables can be arranged so as to make it possible to supply the inspectors with a local color-matching unit, whereas the folders can be supplied with illumination from the ordinary incandescent lamp.

Stockroom.—The layout for this room generally consists of rows of shelves or racks on which the finished goods are placed before being shipped. Since it is necessary to read the labels, which are usually in small print or writing on the tag, a reasonably good intensity of illumination is required. Satisfactory illumination comes from rows of units down the center of the aisle between the racks, a reflector giving a fairly wide spread being usually desirable. Lighting units should be hung at a height so that they will come at least to the top of the shelves and preferably slightly higher—75-watt bowl-frosted lamps in standard dome reflectors or shallow dome reflectors, spaced from 10- to 15-ft. centers, will supply fairly adequate illumination.

Steel Mills.—Interior conditions in steel mills are far different from those encountered in any other industry. In buildings housing what have been termed the rough and medium—rough

operations are usually very large, covering considerable ground area—the widths commonly range from 30 to 100 ft., the lengths from 100 to 600 ft., and the heights from floor line to roof trusses 25 to 60 ft. The roofs are invariably of the steel-truss-supported monitor type. Heavy-duty overhead cranes traverse most of the buildings and are in almost constant operation, carrying heavy machine parts, stock, and incandescent and hot metal in bars and ladles. The atmosphere within these buildings is almost constantly charged with steam created by water coming in contact

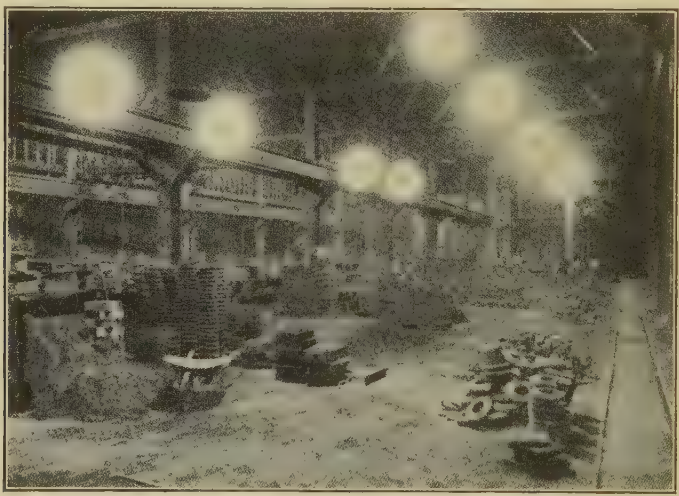


FIG. 190.—Night view of a well lighted foundry. 300-watt Mazda C lamps in RLM standard dome reflectors on centers 10 by 40 ft. are mounted on the ceiling trusses, 35 ft. above the floor. An intensity of over five foot-candles is provided.

with the hot rolls and metal and rising from the water jackets of furnaces, together with graphite particles from the converters and much smoke, ore, and fuel dust. Also by virtue of these same conditions, equipment, and surroundings, floor, walls, and ceilings are dark and sooty, making them decidedly ineffective from the standpoint of light reflection.

The machinery and the equipment are usually widely spread out, covering a considerable part of the floor area, various parts projecting here and there about the areas traversed by the workers. The transfer rolls, cooling tables, and many of the active machine parts are located at a waist-high position. The footing is usually rough, the floor area being broken up by machine parts and material either permanently located or strewn

about during the manufacturing processes. Narrow bridges with steep, abrupt approaching steps, or tunnels entered by steep, narrow stairways, afford the common means of crossing from one side of the buildings to the other. In furnace buildings the equipment is usually lined along the sides, the central floor area being occupied by charging materials, charging machinery, and the various equipment used in processing.

Although it might appear to the uninitiated that almost any type of lighting equipment would satisfy the conditions encountered in the iron and steel industry, careful observation soon indicates that such is not the case. Large areas, high ceilings, dark surroundings, a smoky, dust-laden atmosphere, and, particularly in steel mills, comparatively few workers, considering the spaces involved, are characteristic of all buildings. The dark surroundings make it desirable to use equipment which does not depend upon the walls or ceiling for reflection, but directs its light toward the work. The light, particularly in foundry work, should be sufficiently diffuse to penetrate the molds, but should have enough of a directional characteristic to bring out detail in its true perspective. Too great diffusion will give flat appearance, so much so perhaps that the juncture of different planes may become indistinguishable and cause serious errors in molding.

From a lighting standpoint a rather peculiar condition exists in this industry, in that ample light at the working point, in many operations, is furnished by the incandescent metal undergoing manipulation—as, for example, at the soaking pits, charging and tapping floors of the open hearths and blooming mills. This situation, however, rather than permitting the use of a lower intensity of light, as might seem likely on hasty consideration, actually calls for a somewhat higher value than would otherwise be the case, because the incandescent metal represents sources of high brilliancy, upon which the worker's gaze falls with a greater or less degree of intermittency. If the adjoining areas are dark, the eye does not see clearly and, in fact, is blinded as it moves to the dark surroundings from the bright work, and *vice versa*. The wider the contrast in intensities the greater the degree of readjustment and the longer the time required by the eye to accommodate itself. Thus production is slowed and the accident hazard increased if adequate general illumination is not provided.

The illumination provided should not require undue readjustment of vision and should be of such an intensity that the workman can find tools, inspect and make repairs, carry on his work with celerity and comfort, and be safe from accident, regardless of the presence or absence of hot light-giving metal. Furthermore, the illumination should be free from objectionable glare and so distributed as to prevent harsh, deep shadows.

Natural Illumination.—The variation of natural illumination in large rooms is shown in Figs. 191, 192, and 193.

The curves of Fig. 191 illustrate the values of interior daylight illumination throughout a June day for a typical factory building

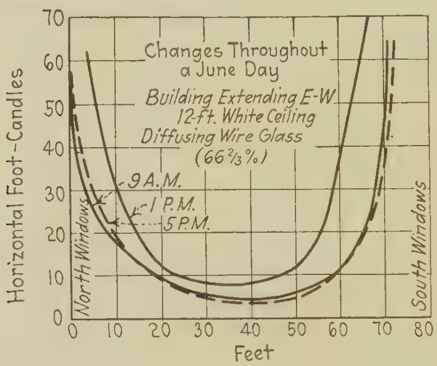


Fig. 191.—Daylight illumination across a building which extends from east to west.

in the latitude of New York City, the artificial illumination of which varied from 3 to 6 foot-candles. The ceiling, walls, and posts were white and the floor of light color.

For comparison, Fig. 192 shows similar data, but in a building extending in the north-south direction. Variations in foot-candles that result in too much light near the wndows, and too little light at the center of the rooms, will be noted.

The higher daylight values prevailing on the upper floors of a building, as compared to those on the ground floor, are illustrated by Fig. 193. Where in positions more than 20 to 25 ft. from the windows, the natural daylight falls to 10 foot-candles or less, it should be possible to turn on general overhead electric lighting units to supplement the daylight. If, moreover, the windows be partially screened, the general lighting is improved in uniformity and some such results as depicted by the dotted curve of Fig. 193 are easily secured.

The usual criteria used in designing windows and rooms for daylighting, namely, that the height to the top of the glass should not be less than half the depth of the room, and that the glass area

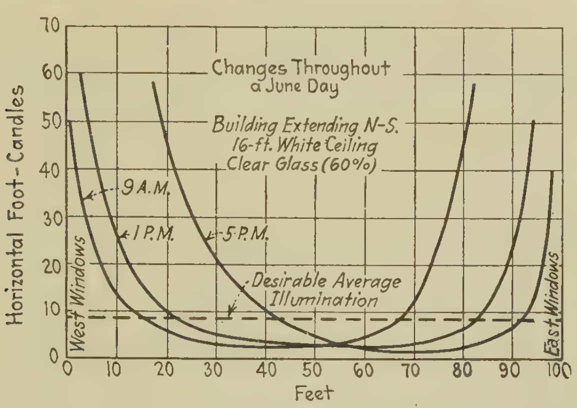


FIG. 192.—Daylight illumination across a building which extends north and south.

should be at least one-fifth of the floor area, are substantially reliable.

In all of the above examples of interior daylight illumination there is a rapid decrease in foot-candles as the distance from the windows increases. In order to obtain the maximum natural

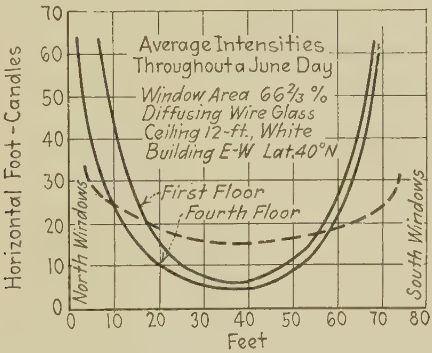


FIG. 193.—Daylight on first and fourth floors.

light in the interior of a building, high windows of diffusing, prismatic, or ribbed glass may be used to advantage.

As a rule, it is better to confine the prismatic glass to the upper sash of a window, as its use in the lower sash is likely to cause glare; moreover, it cuts off the outdoor view.

Most factory owners are particularly interested in making the best possible use of their daylight facilities, so as to render useful and valuable all parts of the floor space, and also to shorten the

Fig. 194.—Saw-tooth roof construction with glass facing the north sky, usually results in well diffused daylight illumination.

periods when artificial lighting is needed. The *saw-tooth sky windows* of modern factory construction (Fig. 194) permit an adequate and nearly uniform daylight illumination of the entire floor area, and are desirable when practicable.

CHAPTER XV

RECREATIONAL LIGHTING

Since indoor sports usually take place in the evening, light other than that required for mere seeing should receive careful consideration.

If the installation is glaring, it will be annoying to the patrons to such an extent as to detract seriously from their evening of sport. If the light is not so distributed as to enable the player to follow up the plays closely or to gage distances correctly, annoyance will again be the result. If the intensity is such as to make exceptional demands on the players' eyesight, in order to follow the ball or the hockey puck, their moods will not be made more cheery. A succession of such faults in the lighting installation may result in the failure of the sport.

Armories.—The *drill hall* is the most important part of the armory and should receive the most attention. The usual form is a large, open space covered with an arched roof. The size of the hall may vary from 100 to 600 ft. in length, from 75 to 300 ft. in width, and from 40 to 120 ft. in height. The roof is often partly of glass to admit daylight, and usually the ironwork is exposed.

The large areas permit the use of high-candle-power units and the lofty ceilings allow hanging heights such that lamps are always well out of the ordinary angle of vision, overcoming any objection which might be raised on the question of intrinsic brightness. The wide range of sizes of type-C lamps available makes it possible to select a unit which will fit any chosen spacing and give the desired intensity of illumination. Inexpensive fixtures, holders, sockets, and reflecting devices are all standardized, thus avoiding the added cost of special designs, which are sometimes necessary in rooms of these magnitudes.

Many drill halls have balconies for spectators, necessitating special lighting below to prevent the dense shadows which would result if only the general lighting was provided.

The uses to which the drill hall is put are somewhat varied. The drilling of raw recruits takes place on only a portion of the

floor and does not require the entire area to be lighted; battalion and regimental drills and reviews necessitate full illumination for ease of maneuvers and inspection; gun drills in the coast defense and artillery sometimes require that all lights be out; or the armory is often rented to charitable organizations and the like for fairs and bazaars, which demand brilliant lighting as well as special decorative or spectacular effects. In any event, sufficient light must be provided in all parts of the room to meet the most exacting conditions.

Fig. 195.—Night photograph of an engineer corps armory (170 by 390 ft., 70 ft., to peak) brick side walls, light green ceiling, pine flooring, lighted by 21 1,000-watt bowl frosted Mazda C lamps in deep bowl porcelain enameled steel reflectors suspended by steel cables. Actual watts per square foot, 0.3—generated lumens per square foot, 6.0.

Since the ceilings are usually broken by trusses and often quite dark, in general, direct lighting is essential.

In most cases it is advisable to use either a translucent reflector or a unit which permits some of the light to escape above the horizontal, for if the ceiling is totally dark the room seems unpleasant. Occasionally, however, the floor is light enough to reflect sufficient light back to the ceiling, even if opaque bowl reflectors are employed.

The type of distribution will vary with conditions. If the side walls are quite dark, a unit giving a wide curve is inadvisable, as

far too much flux will be wasted by wall absorption. With light walls, however, the diffuse reflection will assist in the general illumination, and concentration of the light is not so necessary.

The reflecting equipment consists of:

1. Deep-bowl, dense opal reflectors.
2. Opalescent enclosing globes with large porcelain-enameled steel reflectors.
3. Deep-bowl mirrored-glass reflector.
4. Deep-bowl prismatic reflectors.
5. Deep-bowl and dome types of porcelain-enameled reflectors.

The opaque reflectors prove satisfactory with light-colored floors.

On account of the high hanging employed, some sort of lowering device should be provided for making renewals and for cleaning. A cutout hanger with lowering rope or wire simplifies this phase of maintenance.

The floor varies considerably, depending on the branch of service, cavalry having a very dark-brown tanbark; infantry, light hardwood.

In general, the cavalry and field-artillery armories require less light than those of the other branches of service, as they are not likely to be used for social purposes. This condition is counterbalanced, however, by the fact that the tanbark or loam floor absorbs a great deal of light and makes the place appear abnormally dark.

The roof is usually a dark tone. Lighter tones, varying from white to natural brick, are found as side-wall coverings. The extremely large areas, if finished in a very light tone, would be somewhat annoying, due to glare, but it is desirable that the upper part of the side walls be finished in light colors, even though the lower portion is somewhat darker. This feature would make the lighting considerably more efficient and introduce a certain amount of diffusion. Floors of light-colored woods are advisable from an illumination standpoint.

Lamps of as large size as are obtainable should be used. With incandescent lamps, in general, the larger the lamp the more efficient it becomes. Present practice in armories investigated varied from 300- to 1,000-watt units, the 750- and 1,000-watt sizes predominating.

Gymnasiums.—The *main exercising floor* is usually rectangular, with a moderate-height ceiling. The arrangement most

frequently used has the running track as a balcony 6 to 8 ft. wide around all four sides of the room. In the center of the main floor are the principal pieces of apparatus—horses, bucks, jumping standards, and parallel bars—while the flying rings and horizontal bars hang from the main ceiling. These can usually be pushed aside or drawn up out of the way for basket ball, indoor baseball, and wrestling matches or practice.

The center part of the space requires even illumination of a moderate intensity, with lamps so located that the hanging appa-

Fig. 196.—Night photograph of a gymnasium 60 by 120 ft., lighted by 400-watt clear Mazda C lamps in semi-enclosing units consisting of a diffusing glass dish suspended beneath a large porcelain enameled steel reflector; 1 watt per square foot is provided.

ratus will not cause dense shadows. Particular attention should be paid to shielding the eyes from the lamp filament, for it is necessary to look upward a great deal when playing basket ball and to face the ceiling often in ring and bar work. A blinding effect is particularly serious at such times and may cause a bad accident.

The illumination below the track need not be so high as in the open space, yet in many cases it is necessary to provide a few outlets here with small lamps properly shaded to prevent dense shadows.

An investigation of twenty-two gymnasiums equipped with modern lighting systems showed that the following types were employed:

Enamel steel, dome shape, 7.
Enamel steel, deep-bowl shape, 1.
Mirrored glass, deep-bowl shape, 4.
Prismatic glass, deep-bowl shape, 2.
Opalescent glass, flat type, 2.
Opalescent enclosing globe, 3.
Opalescent enclosing globe with enamel steel reflector, 2.
Opalescent glass semi-indirect dish, 1.

In these twenty-two buildings the minimum wattage per square foot was 0.42; the maximum, 2.0; the average, 0.78. The average generated lumens per square foot amounted to 9.0. As most of the equipment employed is of an efficient character and side walls are generally light, varying from white to natural brick, and the ceiling, in contrast to the dark ceiling of the armory, usually also light, a fair average figure for the intensity of the illumination provided is between 4 and 5 foot-candles.

In some instances, the ceiling of the room is of such character that deep-bowl, mirrored-glass reflectors can be recessed, so that the mouths of the reflectors are flush with the ceiling. This arrangement directs light strongly downward; lamps are not visible unless one looks directly upward and there is no danger of breakage.

Sometime when opaque reflectors are used for direct lighting a number of small lamps are also provided in inverted reflectors which direct light to the ceiling and prevent this from being totally dark.

Where direct lighting with opaque reflectors is employed for the main portion of the floor, it is sometimes advisable to utilize bowl-shaped opalescent-glass units beneath the running track or balcony. These provide good illumination on the side-wall apparatus and at the same time emit some light in a horizontal direction, overcoming the "dead" effect which results if only strongly directional light is employed.

Swimming Pool.—This room, from a lighting standpoint, is practically a modified Ulbricht sphere, for the side walls and the ceiling are generally white tile. The type of reflecting device employed makes but little difference in the illumination. Care should, of course, be taken to insure satisfactory eye protection.

An examination of eight pools using the following reflecting devices, namely, prismatic-glass bowl, opalescent-glass bowl, mirrored-glass bowl, and enamel-steel reflectors, showed the watts per square foot employed to vary from 0.3 to 0.7, with an average of 0.5.

The Running Track.—Although in most cases this extends about the main exercising room and the general illumination is sufficient for the track, sometimes a long track is installed in the form of a low tunnel. For such conditions, angle-type reflectors pointing in the direction the runner is proceeding avoid any likelihood of glare and direct the light where it is required.

Miscellaneous Exercising Rooms.—These comprise the wrestling, boxing, and fencing rooms, together with the medical director's office. Fencing requires a relatively high intensity of illumination, and it is probable that one room only will be provided for all these sports. In such cases the lighting layout must be considered from the standpoint of fencing.

Since the action is rapid, it is essential that the light be well diffused and of high intensity in order that all movements may be readily followed.

These rooms are usually finished in light colors, with smooth ceilings, making indirect and semi-indirect systems of illumination quite feasible. Approximately 1 watt per square foot of floor area with type-C lamps proves satisfactory with semi-indirect lighting. As the rooms are often decorated with prizes, pennants, etc., the decorative element of the fixture is important.

The medical director's office presents the ordinary problems for office lighting as well as the necessity for plenty of light in all parts of the room for physical examinations. Totally indirect or dense-glass semi-indirect units are suitable.

Pool and Billiard Parlors.—When considering the lighting requirements for pool and billiard tables, two important points must receive careful attention: high intensity and extremely good diffusion. The necessity for this is easily seen from the fact that the playing area is rather small and distances and angles must be carefully gaged. A shadow cast by a ball is very apt to mislead players in gaging distances, or otherwise disconcert them, causing them to fumble the shot. No shadows cast by players standing in the immediate vicinity of the table should be allowed to fall on the table, unless these shadows are so soft as to be imperceptible.

There are three methods by means of which these requirements can be met in a satisfactory manner:

1. Individual units located over each table, supplemented by a low intensity of general illumination.
2. Translucent reflectors placed over each table which serve both as local light for each table and general lighting for the entire room.
3. A straight general system employing semi-indirect, indirect, or enclosing diffusing units.

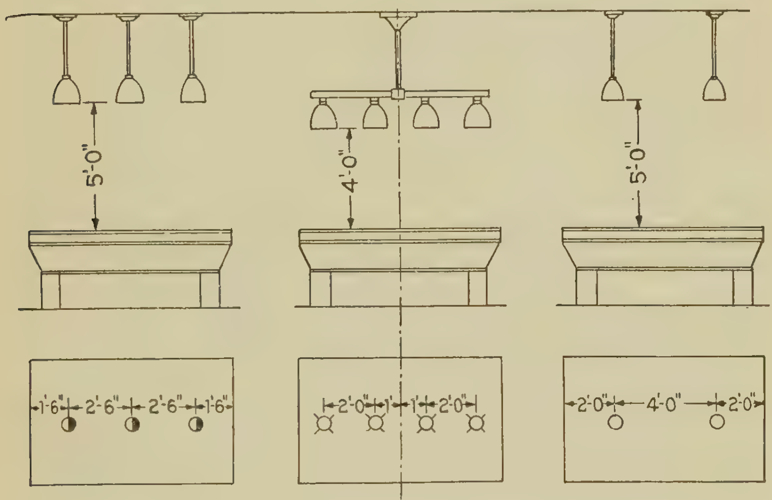


FIG. 197.—Three common methods of lighting billard tables.

Individual lighting of tables is by far the most common method. The units should be hung high enough so that they do not interfere with the players' movements, and are not likely to be struck with a cue. It is necessary for the reflectors to be of such type that the angle of cut-off of light from the lamp is fairly sharp and no direct light is permitted to enter the player's eyes. A medium intensity of general illumination is necessary with such a system, and this can best be obtained by using 100- or 200-watt type-C lamps in indirect, semi-indirect, or enclosing units, spaced to provide from 0.25 to 0.5 watt per square foot of floor area.

Figure 197 shows three schemes for the local lighting of tables and Fig. 198 shows a night view where the local lighting is supplemented by general illumination of the indirect type. The con-

struction of these particular fixtures is interesting, all four units being served from one outlet.

Where translucent reflectors are empoyed, there is frequently no necessity for additional general lighting units. Special attention should be paid to the size and the type of the glass reflector to eliminate the possibility of glare.

General lighting, properly installed, will give better results and present a neater appearance than a combination of local and general, or purely local, lighting.

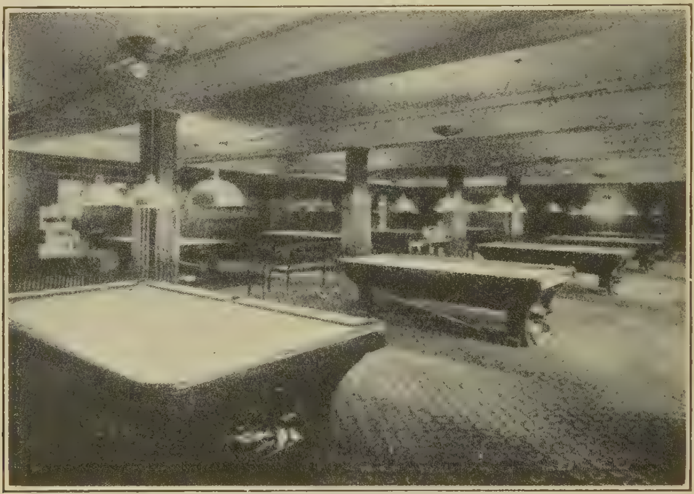


Fig. 198.—View of a hotel pool room showing lighting installation consisting of three 40-watt Mazda B lamps in copper dome reflectors over each table. General lighting is provided by Mazda lamps in indirect units. The white finish of the ceiling is a great aid in diffusing the light from these units, thus creating soft shadows.

With the indirect system, because of the diffusely reflected light from the ceiling and walls, the placement of tables with regard to the lighting units is not important.

The semi-indirect system requires more careful placing of units with respect to tables in order to keep shadows short and soft. Best results are obtained with this system when a group of tables are to be lighted, as the units can then be so placed as to make tables receive predominating light from several directions.

While enclosing units diffuse the light to a certain extent, still most of the light received under such a system is direct light, and hence particular care must be used in placing the units so that objectionable shadows will not interfere with the player's aim.

Bowling Alleys.—The very nature of bowling is such that unless careful consideration is given to the proper shielding of light sources, it is very likely that the pastime cannot be carried on with any degree of enjoyment. Bowling alleys, by virtue of their construction, are long, narrow areas with comparatively low ceilings, which practically limit the spacing of outlets to the region above the alleys themselves, where the lighting units are most conspicuous. It is obvious that, unless they are properly

FIG. 199.—Lighting of a bowling alley, enclosing-diffusing luminaires for general illumination, angle-reflectors for lighting the alleys.

shielded, the resulting glare may be such as to render the player unable to aim his ball effectively.

The intensity on the alley itself should be fairly high, while at the end, on the pins, the intensity should be approximately double that on the alley.

The best method of obtaining an evenly distributed light on the surface of the bowling alley and a high intensity on the pins, free from glare or glaring reflections, is to utilize 40-watt lamps in angle reflectors mounted in a single line over the center of the alley, as shown in Fig. 199.

This system can be used for lighting two alleys, and when so employed, outlets for 60- or 75-watt lamps with the proper-

size angle reflectors should be spaced in a single line, midway between the two alleys, with individual units on each alley at the pins.

Outdoor Sports.—Attention is also being given to artificial lighting for outdoor sports, such as tennis, golf, football, etc., with successful results.

Tennis Courts.—The conditions to be met in the lighting of outdoor courts present problems not encountered in other fields

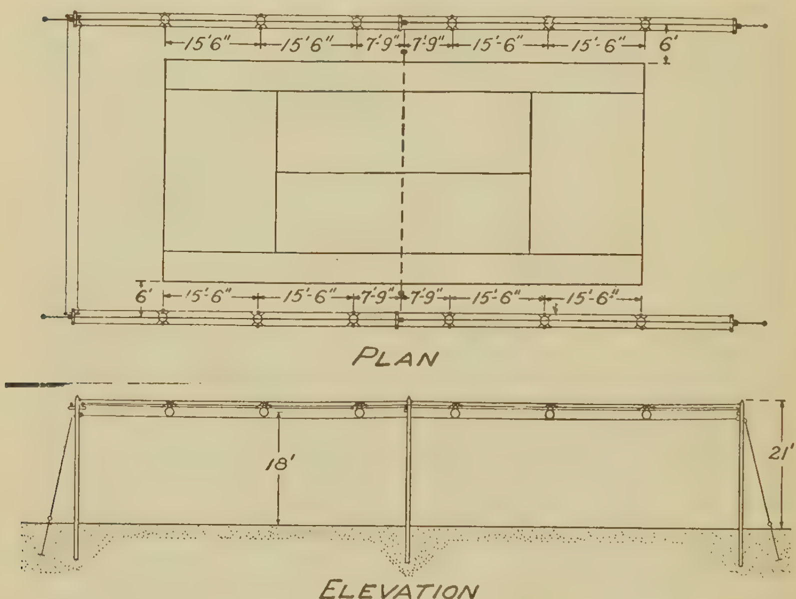


FIG. 200.—The arrangement of 500-watt Mazda C lamps with angle type enameled steel reflectors in the side lighting system for tennis courts.

of illumination. There is no fixed plane, and the light must be distributed in such a manner that the ball is well lighted during its entire travel.

The conditions to be met in order to secure a well-lighted tennis court may be thus summarized:

1. The entire surface of the court must be lighted evenly to a high intensity. An evenly lighted court is necessary, as the ball apparently changes its speed when passing through sections that vary in intensity. A fairly high intensity is essential, as the game is played rather rapidly and requires sufficient light to allow the player to follow the ball readily.

2. The glare from light sources in the direct line of vision must be avoided, as this interferes with seeing. If, when following the ball after a stroke, one is forced to look at a lamp, the ball becomes lost to the vision and a short time elapses before the eye reaches its normal condition. Obviously, any lights at the end of the court are objectionable.

3. The distribution of light from the lighting units must be such that the ball will be illuminated by direct light at a height of approximately 20 ft. Above this height, the reflection from the court surface will illuminate the ball sufficiently, for at this height the ball is usually traveling comparatively slowly.

4. The entire installation must be so arranged as to eliminate any danger of interference with the play. The lighting units

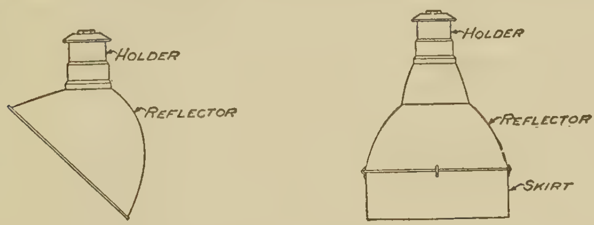


Fig. 201.

Reflector for side lighting system. Reflector for overhead lighting system.

themselves must be at a sufficient height, or a sufficient distance from the side lines, to be out of range of the ball. The supports (posts, etc.) must be so located as not to interfere with the player both at the side lines and at the run-back.

The power required varies with the system in use from 4,000 to 6,000 watts. Counting a reasonable return on the investment, and allowing for lamp renewals, the cost of lighting tennis courts is well below the amount that would be spent for playing pool or billiards.

The two methods generally employed for tennis-court lighting have been designed to meet the requirements outlined above. Practically all artificially lighted tennis courts use one of these two systems, although several modifications are possible.

In the side-lighting system units are hung at a moderate height along the sides of the court, while in the overhead system they are placed far above the ground over the center line of the court. These two systems are the result of considerable experimentation, and have been found very satisfactory.

The side-lighting system is shown in plan and elevation in Fig. 200. It calls for twelve units, six on each side of the court, spaced and hung as shown; 500-watt lamps are used with suitable angle-type porcelain-enameled reflectors and weatherproof holders. Figure 201 shows a typical reflector which gives the required distribution of light.

The overhead lighting system in plan and elevation is shown in Fig. 202. This system calls for four 1,000-watt lamps equipped with deep-bowl enameled-steel reflectors and special skirt with weatherproof socket holders, as shown in Fig. 201. They should be placed as indicated in the dimensioned drawing.

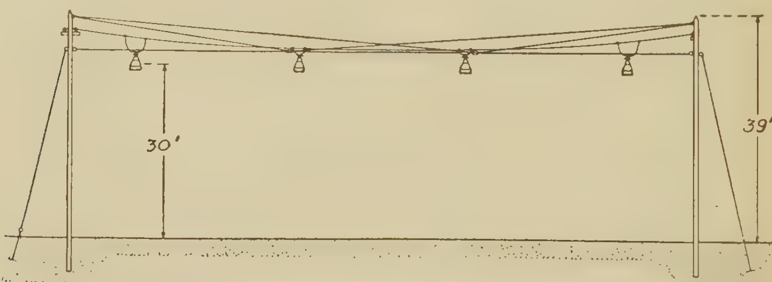


Fig. 202.—Tennis court overhead system. Location of 1,000-watt Mazda C lamp with bowl-shaped enamel steel reflectors.

Golf.—The night lighting of a golf course has been demonstrated to be thoroughly practical not only in driving and putting, but in playing the complete hole. An installation at Briarcliff Lodge, N. Y.,[1] proved very satisfactory and a brief description of the system on the first fairway and green will be given.

The hole is 246 yd. distant from the tee. Two pole lines were erected, one on either side of the fairway. On the two poles nearest to the green, on either side, were mounted two 1,000-watt X-ray floodlights, all directed on the green itself. Supplementing that, taking advantage of the natural lay of the land, seven similar flood units were installed about 125 yd. back from the green toward the tee, with only two or three of them directed on the green, the remainder being thrown into the air to light the path of the ball. Back 75 yd. further toward the tee another group of five units was installed, directed into the air. Thus there were only about half of the units, or ten 1,000-watt floods, directed on the green, the remaining ten lighting the airpath,

[1] *Trans. Illum. Eng. Soc.*, vol. 19, p. 882.

which gave a total of 27 kw. in floodlighting equipment, taking care of the entire fairway and green.

The plan of the installation is shown in Fig. 203. The general scheme of floodlighting was supplemented by small units, placed back of the green, lighting the trees and shrubbery in color.

It is suggested that a phosphorescent ball may prove helpful, especially when driven out of the range of the light beams or into the rough.

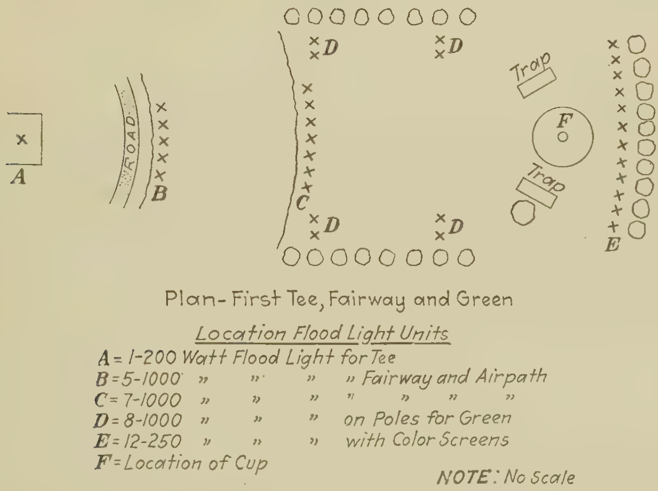


FIG. 203.—Artificial lighting for a golf course.

The Lighting of Outdoor Arenas.—The illumination of outdoor areas sufficiently large to be used for auto polo, drilling, football, hockey, skating, playgrounds, and athletic contests in general offers exceptionally interesting problems.

Three methods of illumination are employed, as follows:

1. Suspending units over the area by messenger cable strung between poles. The units must be hung at a sufficient height to eliminate any danger of glare to either the observers or the players. The spacing must be such that the illumination is reasonably uniform for the hanging height and type of reflector employed.

2. Lighting from units located at the sides, employing standard angle-type reflectors. These must be suspended at such a height and in such positions as to prevent the possibility of annoyance to the players and to observers in the stand.

3. The employment of floodlighting projectors located on the roof of the grandstand, adjacent buildings, special poles, or even trees.

Each system has certain advantages, and the one to be selected will depend upon the area to be lighted and local structural conditions.

If the field is comparatively small and only a low intensity is required, as, for example, a small drill field, skating pond, or playground, poles can be erected without difficulty. The overhead system employing medium-size lamps with standard distributing reflectors is probably the most simple installation.

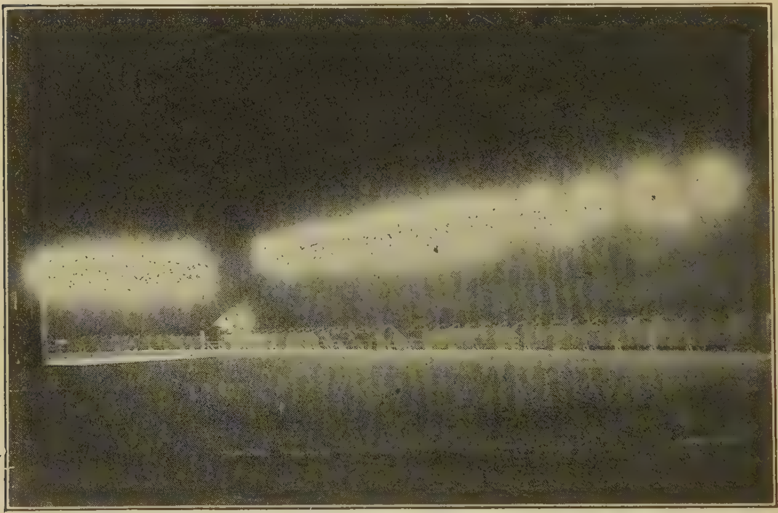


Fig. 204.—Night view of a horse show arena lighted by twenty-two 1,000-watt Mazda C lamps with angle steel reflectors placed above the grandstand.

Where there is a grandstand or similar structure and the area to be lighted is comparatively narrow, angle-type reflectors fitted with standard lamps are inexpensive and easily installed. An example of such an installation is to be seen in Fig. 204. This particular arena was used in the evening for acrobatic acts, chariot races, zouave drills, auto polo games, and the like. It can be readily seen from the photograph that the lighting results were quite satisfactory, although slightly less than 0.4 watt per square foot were employed.

For lighting areas too wide to permit the use of the overhead system, and when only a low intensity is required, angle-type

units located on poles around the edge of the field as pictured in Fig. 205 prove satisfactory. They are much less expensive than floodlighting equipment.

Where the area to be lighted is wide and a relatively high intensity of illumination is desirable, floodlighting equipment offers the best solution. The type of floodlighting projector employed will depend on the available means of support and the distance between units.

Football Fields.—A football gridiron was successfully lighted on Nov. 21, 1923, when a thoroughly successful night football game was played at Lynn, Mass. Eight 18-in. searchlamps and fifty "L-15" projectors mounted 42 ft. above the ground were used. The intensity varied from 4 foot-candles in the center of the field to 1.25 at the sides. All the lamps used consumed 1,000 watts each at 110 volts and were of the gas-filled type.

The location of the units with reference to the field is shown in Fig. 206, and the direction of the beams of light indicated by the lines radiating from the units. The beams from the searchlights, however, were projected into the sky, illuminating the region above the field. It is probable that these units will be replaced by additional floodlights directed toward the zenith in future installations. The floodlights at 1, 2, 5, and 6 used clear glass and those at 3, 4, 7, and 8 employed stippled glass.

Summary.—The following table gives the desirable intensity for various outdoor sports:

TABLE 39

	Intensity in foot-candles	Watts per square foot[1]
Drilling:		
Small areas	0.5–1.5	0.07–0.22
Large areas	0.1–0.3	0.02–0.05
Football	1.0–2.0	0.15–0.30
Hockey	2.0–3.0	0.30–0.50
Polo:		
Horse	1.5–2.5	0.2 –0.40
Auto	1.0–2.0	0.15–0.30
Skating	0.25–0.75	0.03–0.10
Playgrounds	0.25–0.75	0.03–0.10

[1] Based on use of high-power type-C lamps and efficient reflectors.

FIG. 205.—Night view of a drill field lighted by nine 750-watt Mazda C lamps in angle steel reflectors on poles around the edge of the field.

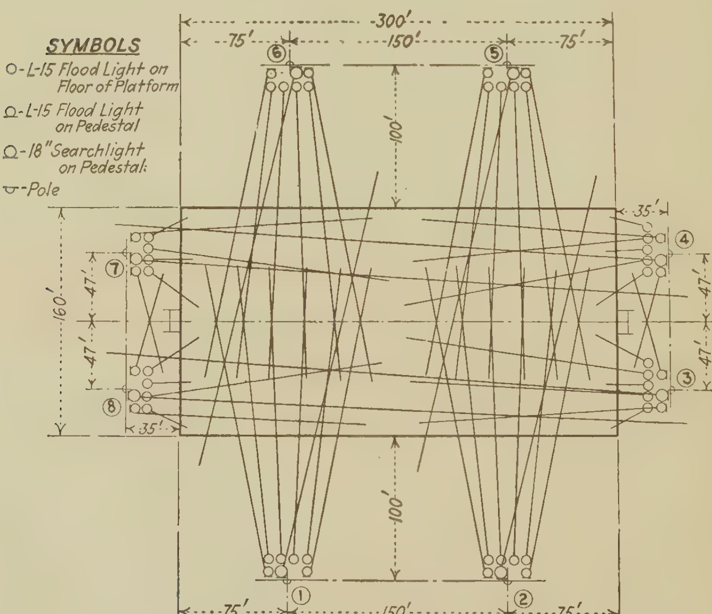


FIG. 206.—Layout of lighting units for football field.

In common with indoor installations, careful maintenance is necessary if the best results are to be obtained. The units employed should always be of a weatherproof type, not subject to deterioration with the action of the elements.

As with any device used out of doors, special attention must be paid to durability and strength. The force of the wind, the weight of accumulated snow, and such tend to loosen fastenings, and unless precautions are taken the swaying motion soon causes minute cracks to appear in porcelain-enameled or other protective surfaces. Moisture seeping through these surfaces attacks the base metal with disastrous results.

CHAPTER XVI

PRINCIPLES OF STREET LIGHTING[1]

The objects of a street-lighting system, aside from the personal convenience of seeing the way at night, are to reduce crime and accidents, to speed up traffic, to increase civic pride, and to stimulate business and other activities which may be carried on by artificial light.

Like interior lighting installations, the lighting of each street involves problems peculiar to itself. No definite rules can be compiled which will apply even to streets of the same class. In order, then, to be able to design a street-lighting system to give satisfactory results, it becomes necessary to understand the underlying principles and fundamental considerations of an effective street-lighting installation.

A thoroughly effective street-lighting system is difficult to define, but when such a system is studied it will be found that the illuminants are located and placed suitably, mounted at a desirable height, and enclosed or equipped in such a way as to present to the eye a desirable combination of candle power and brightness for the lighting unit and a distribution of light along the street and upon the buildings.

Observation and experience indicate that moderation is generally desirable in street lighting. Moderate-sized lamps—equipped so as to modify the distribution of light and to make for uniformity of illumination—moderately bright, moderately spaced, and at moderate heights lend themselves to successful street illumination in most cases. Departure toward either extreme in any particular may be justifiable and may be desirable, but, in general, moderation is the best rule of practice.

Night Vision.—Objects are perceived at night by reason of contrast in brightness.

1. Objects are seen as silhouettes when they are markedly different in brightness from their backgrounds.

[1] The author wishes to acknowledge the several excellent papers on this subject by P. S. Millar.

2. Objects are perceived when the exposed surface of an adequately illuminated object presents areas of different reflecting powers, or elements more or less favorably inclined with respect to incident light, or elements which lie in the shadow of other elements of the surface.

3. Objects may be perceived by reason of the shadows produced by the interception of sharply inclined rays of light.

Color contrast is of little use, since with intensities where discernment is at all difficult color is usually lost and objects are perceived more readily by other means.

The majority of observations of large objects on the streets in the more intensely lighted thoroughfares, especially by automobile drivers, are as silhouettes against the bright street or building background, because a driver is concerned primarily with avoiding obstacles and usually looks carefully enough only to detect the presence of pedestrians and other objects. Usually, he sees these as dark objects silhouetted against the lighter surfaces. The pedestrian, too, obtains distant views of large objects as silhouettes, but as he moves more slowly and approaches objects more closely, he has opportunity for closer observation, and in the more brightly lighted streets supplements discernment by silhouette with actual observation of surfaces in relief.

Glare.—The effect of glare in street illumination is dependent primarily upon:

1. The extremes of contrast within view; that is, contrast in brightness between the light source and the illuminated surfaces.

2. The visual angle separating the glaring source from the observed surfaces.

3. The portion of the field of view which is illuminated.

Glare militates against good street illumination, first in decreasing ability to see, and, second, in rendering unpleasant the appearance of the installation and the street. In so far as glare reduces visual power, it manifests itself in three ways:

1. Actual diminutions in ability to perceive small contrasts in the presence of a bright light source.

2. Distraction of attention, as a result of which small contrasts may not be perceived when viewed casually.

3. A temporary dazzling effect which persists for a few moments after a bright light source is viewed directly.

Figures 207 and 208 illustrate the effect of glare. In Fig. 207 the nearby light source is removed. In Fig. 208 the presence of

the light source distracts attention from the automobile and the view is rendered less pleasant. In fact, there is a little discom-

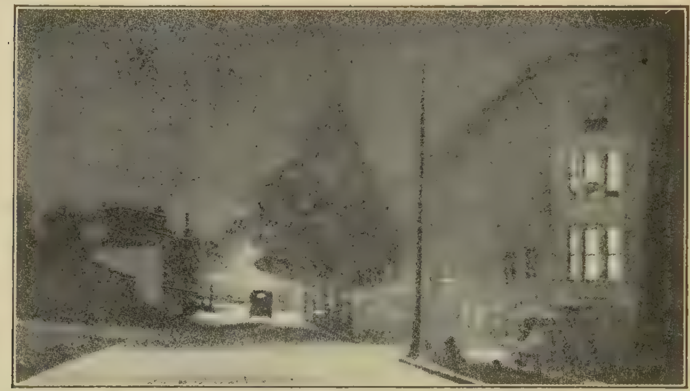


FIG. 207.—Street lighting by silhouette effect. Illustrating importance of bright street surface and showing how the automobile is discerned because the street surface beyond it is bright, not because the light falling upon it renders it visible. For a demonstration of glare see Fig. 309.

fort involved in looking at the automobile. Nevertheless, if one deliberately dispels the idea of the glaring source from his mind and concentrates on the automobile, it can be seen

FIG. 208.—Same as Fig. 207 with nearby light source visible. For a demonstration of the importance of separating the glaring source from the observed object hold the picture nearer to or further from the eyes, as the distance from the picture to the eyes becomes greater the visual angle of separation becomes less and the glare effect is magnified.

just as well in either illustration. These pictures further illustrate the importance of securing adequate separation between the light source and the observed object, the distraction due

to the light source being greater relatively when the picture is held at a distance from the eye and the visual angle between the source and the object is decreased.

Other studies are presented in Figs. 209 and 249. Figure 209 shows the effect of placing a lamp on the inside of a curve. The glare obscures the road beyond. Figure 249 shows the improvement in placing the lamps on the other side of the curve, as well as the effect of other lamps in the field of view as mentioned below.

If a single brilliant light source, as a bare type-C lamp, is located over a dirt road in the country, the glare is very bad.

FIG. 209.—View of country automobile road. Lamp wrongly located on inside of curve. Glare obscures view of road beyond.

If the lamp is raised to a greater height or moved to one side of the road, or if the lamp is enclosed in a diffusing globe, the glare is lessened. If a number of additional lamps are strung beyond it along the road, the glare is further reduced. If the lamps, instead of being located over a dirt road, are located over a treated macadam road, or, better still, over an asphalt road, the glare is less serious. Light-colored buildings along the street also assist in reducing the glare. In short, anything which reduces the contrast between the light source and the road surface, or which increases the illuminated area within view, or which separates the bright light source from the road surface reduces the effect of glare.

The relationship between candle power and brightness of source, and the relationship of these to location and background in street lighting, are not well understood. Attempts to measure and evaluate such effects have proved unacceptable. In none of them has the subjective element been eliminated or brought under adequate control. No way has been found to reproduce for test purposes the conditions of attention which obtain in the ordinary use of the street by drivers and pedestrians, nor have means been found to evaluate the feeling of satisfaction and contentment with one lighting system which may not be experienced with another lighting system when the latter cannot be said to produce serious glare which can be measured in visual tests, but is still unsatisfactory as to brightness or candle power in the direction of the eye.

The problem resolves itself, in the main, into a means of delivering sufficient light upon a street without producing serious glare. The usual means employed are to mount illuminants at a moderate height and employ sufficiently large globes to keep the brightness below the point which produces serious glare, or else to mount the lamps high with a view to removing them from the center of the field of vision, employing some means of directing the light downward upon the street.

Good practice appears to indicate as less light is available for streets, it becomes more important to employ equipment which is designed to direct it along the street, to the exclusion of the sides of the street. Conversely, when ample light is available, unnatural and dissymmetrical light distributions become unnecessary and buildings along the street may be lighted as well as the street surface with advantage to visibility conditions and to the appearance of the street.

When lamps of moderate or large size are mounted at relatively great distances apart, the only way to approach uniformity of lighting is to redirect the light along the street, with a large excess at angles slightly below the horizontal, in order to deliver enough light midway between lamps to render the illumination in such areas comparable with that nearer the lamps. This can be accomplished only at the expense of such high candle power and brightness at angles slightly below the horizontal as to occasion serious glare at any practical mounting height. The superiority of substantially uniform illumination over a moderate diversity, resulting from more natural light-distribution charac-

teristics, is usually insufficient to compensate for the attendant condition of glare.

Location of Lamps.—For effectiveness in illuminating streets, there is no location quite so favorable as directly over the driveway. Where the lamps are few and far between and of small size, and where the pavement is of asphalt or other material which tends to take a polish from motor traffic, the advantages of locating the lamps over the driveway are greatest. When the lamps are numerous and of large size, and the street illumination is of high intensity, the precise location of the lamps is of less importance, since the greatest revealing effectiveness does not have to be obtained from them.

When a relatively large amount of light is produced, effectiveness of utilization may be sacrificed somewhat to secure improved appearance. With lamps located over each curb, the street appears much wider, which is usually desirable, and the sidewalks and the fronts of buildings are better illuminated. When, however, the lighting of the roadway becomes of first importance, as in streets of the highway class, the best use may be made of the light by locating the lamps as nearly as practicable over the roadway, so as to take full advantage of all specular reflection from the street surface.

Spacing.—Lamps should be close enough together to avoid dark areas between them. On the other hand, it is neither necessary nor desirable to reduce the spacing intervals sufficiently to approximate uniformity of illumination along the street. Since discernment in the street at night is largely dependent on contrasts of light and shadow, contrasts are diminished when uniformity is attained through multiplicity of small illuminants through the elimination or reduction of shadows. Objects on the street and depressions in the street are not seen so well as they are when lighted from fewer, larger lamps. These, though failing to provide uniformity of illumination, do produce relatively strong shadows, which are an aid to visibility.

Mounting Height.—The height at which lamps may be installed depends upon the character of the street, the equipment on the lamp, and the nature of the surroundings. In many of the latest installations, high-candle-power lamps are located 14 to 18 ft. over the curbs on business streets. These, however, are usually backed by light-colored buildings, show windows, and illuminated signs, which together with the head-

lights of automobile traffic render glare from the street lamps unobjectionable.

Where the sky, foliage, or dark-colored buildings form the background, the opportunity for glare to become serious is considerable. Improvement will be realized by placing the lamps higher, equipping them with larger diffusing globes to lower the brightness, and possibly decreasing the candle power of the unit.

Much improvement will be found by removing the lamps a very few feet when they happen to be near the line of vision.

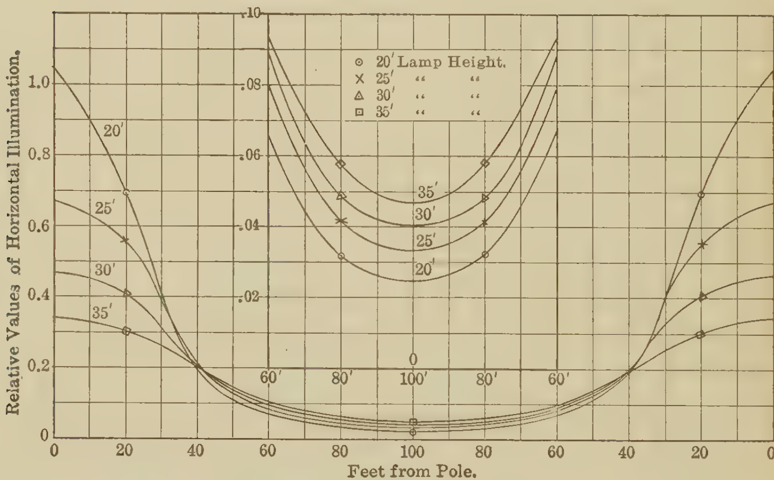


FIG. 210.—Illumination between lamps placed 200 feet apart. (Arc lamps, opal globes.)

The curve of glare falls off rapidly with increasing separation when the separation between the light source and the observed surface is only a few degrees. Around a lamp which has a dark background, there is a zone of halation, within which objects tend to become invisible. Once outside this zone, the glare effect falls off rapidly. It is very important to mount the lamps high enough to insure that the separation from the street surface is at least sufficient to avoid this zone of serious glare.

The effect of a change in the height at which the lamps are placed upon the value and distribution of illumination is shown in Fig. 210. It will be seen that increasing the height greatly increases the horizontal illumination midway between the

lamps. The ratios of maximum to minimum for two lamps having typical distribution curves, at the four heights are as follows:

TABLE 60

Height of Lamps	Ratio of Maximum to Minimum
20	43 to 1
25	21 to 1
30	11.5 to 1
35	7.5 to 1

Control of Light.—Much planning and design has been influenced by a desire to approximate uniformity of illumination along the street. Other aspects of street-lighting effectiveness should not be sacrificed to secure a considerable percentage increase, but, rather, a small absolute increase in illumination midway between lamps. Such improvement in midpoint illumination can be had, of course, only at the expense of largely increased candle power just below the horizontal. To avoid glare as a consequence of such light distribution, the units have sometimes been mounted high. The resultant effect upon the illumination curve has been thought to be good.

It must not be forgotten that, as lamps of symmetrical horizontal distribution are mounted higher, the proportion of light flux delivered upon the street surface is diminished. This effect is increased if the candle power just below the horizontal is made larger to reinforce the illumination midway between lamps. These relations are illustrated in Fig. 211. Considering the total light produced, a smaller part is delivered below the horizontal from a diffusing globe unit than from a bowl refractor, and the amount on the street favors the latter. If, however, some of the light is desired above the hori-

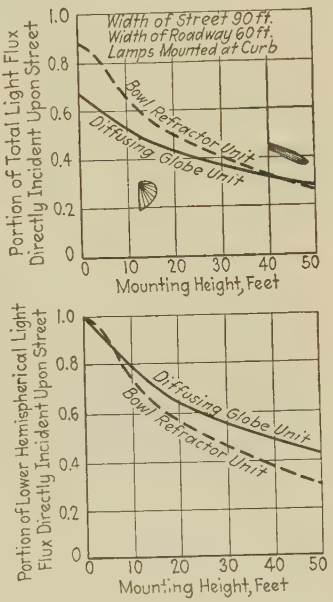


FIG. 211.—Light flux incident on street for different heights of suspension when the unit is equipped with bowl refractor and diffusing globes.

zontal and the lower hemispherical light flux alone is considered in this relationship, the relative proportions delivered upon the street surface are shown by the two lower curves, the bowl refractor delivering a smaller proportion of flux from all practicable mounting heights.

This consideration apparently has entered into the design of two-way, four-way, and asymmetrical reflectors and refractors, described later, which are intended to deliver larger proportions of the light along the street by utilizing the light which otherwise in some installations would be wasted or used to poor advantage in other directions.

Glassware.—One of the most important parts of a lighting unit is the glassware. To lower the brightness of the source a globe having good diffusing properties should be used. The efficiency is affected by the type of fixture used, the size of the reflector, and the nature of the reflecting surface, and also by the thickness, density, and quality of the glassware. The glassware protects the lamp from rain and snow and adds to the appearance of the unit.

Fig. 212.—Prismatic glass refractors for street lighting. A, band refractor for lamp sizes from 1,000 to 10,000 lumens. B, bowl refractor for lamp sizes from 1,000 to 10,000 lumens. C, dome refractor for lamp sizes from 1,000 to 10,000 lumens.

The choice of glassware will depend on whether the utilitarian effectiveness or the aesthetic value is of primary importance. Various kinds of glass are used for globes and each kind may be obtained in different weights and densities. Some of the factors influencing the transmission of light are the shape of the globe, thickness of glass, density of the diffusing media used in the manufacture, as well as the quality of the glass base itself and the personal element entering into its manufacture.

Table 41 gives data on globes similar in shape to the one shown in Fig. 227 and varying in height from 12 to 14 in. and in overall diameter from 13 to 16 in.

TABLE 41
Light Transmission Loss in Globe

Kind of glass	Density rating	Weight		Per cent loss
		Pounds	Ounces	
Crystal	Clear	10	8	9.1
Alba	Light	10	12	19.0
Carrara	Light	11	4	17.9
Carrara	Medium	12	12	31.2
Alabaster	Light	9	8	17.9
Alabaster	Medium	10	0	27.9
Polycase	Medium	11	4	28.8
Monax	Light	4	12	22.2
Genco	Light	4	14	23.9
Genco	Light	4	12	22.2
Rippled	Clear	11	9	8.7
Rippled	Clear	6	7	8.5
Rippled	R. I. & R. O.	6	11	22.3

The rippled globe may be of clear glass with a rippled surface and acid-etched finish, or it may be of glass with a light flashing of opal or alabaster with a rippled surface. These globes give to the light from an incandescent lamp a sparkle and a brilliancy

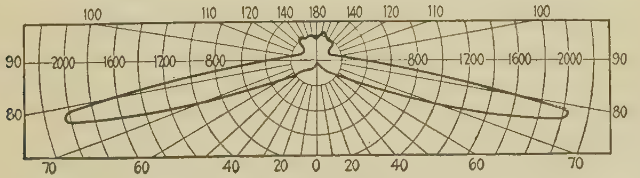


FIG. 213.—Candlepower distribution showing greatest intensity in a plane about 22½ deg. from curb line.

which is preferred by many people. They also diffuse the light fairly well and have low absorption.

Prismatic refractors, sometimes used on street lamps to redirect some of the light from directions where it is not needed to the

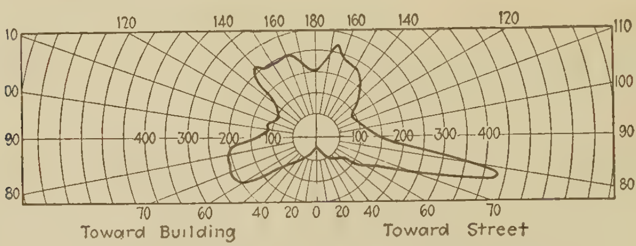


FIG. 214.—Candlepower distribution in a vertical plane at right angles to curb line indicating the low intensity toward residences.

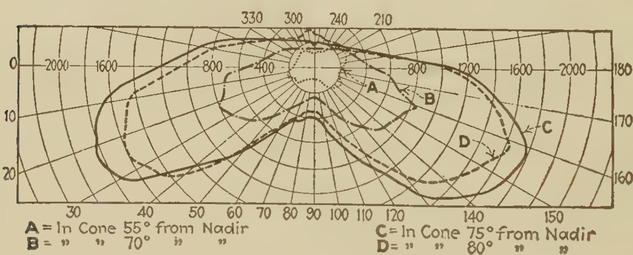


FIG. 215.—Laboratory tests of lateral candlepower distribution in cones varying from 50 deg. to 80 deg. from the nadir.

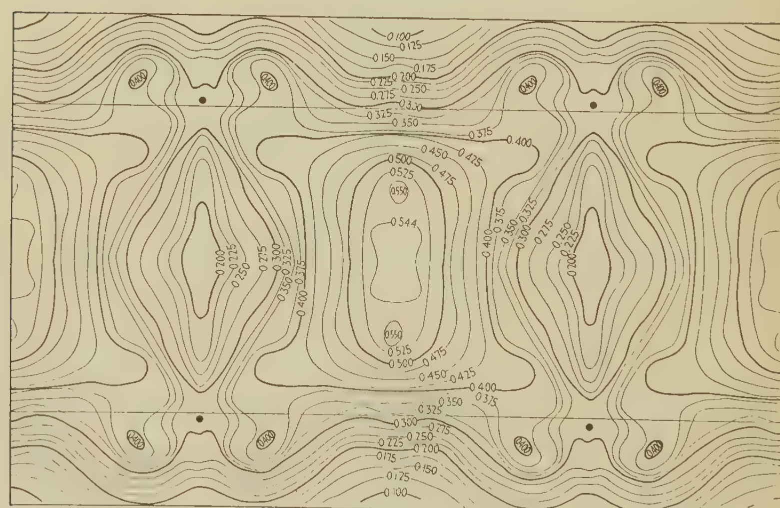


FIG. 216.—Isolux curves with "bi-lux" refractor, producing asymmetric distribution with 6,000 lumen lamps mounted on 14-ft. posts 100 ft. apart.

roadway, or where it will be more useful, are shown in Fig. 212. These reflectors usually have horizontal prisms on one side to modify the distribution of light in the vertical plane, and vertical prisms on the other surface to throw the light up and down the street and take it away from the sides.

A more recent type of prismatic refractor for a symmetric street illumination consists of two cylindrical elements, nested together, the horizontal prisms being on one element and the vertical prisms on the other. This is known as the Bilux refractor. Distribution curves for this unit when equipped with a 4,000-lumen lamp and under laboratory conditions are shown in Figs. 213, 214, and 215. The isolux curves in Fig. 216 are for 6,000-lumen lamps.

Nature of Street Pavement.—The modern streets which require the greatest care in lighting are those traversed by automobiles. The majority are paved with asphalt, asphalt block, wooden block, treated macadam, etc. As a result of automobile traffic, such pavements become oiled and polished. The surface reflects specularly and its brightness is due largely to distant lamps.

The horizontal foot-candle intensities on upper Seventh Avenue, New York City, a street much traversed by automobiles, was found to vary in the ratio of 10 to 1, while the effective brightness at the angle of the automobilist's view was in the ratio of 2 to 1. The impression of uniformity which one receives from a trip along the street is produced by this brightness ratio rather than by the foot-candle ratio. On this street, which is of the boulevard, central-parkway type, there are three lines of lamps. The linear spacings of the lamps are about 125 ft. As the street is fairly level, a great number of these lamps are within view at a given time. The street surface consists largely of small polished areas which reflect specularly.

CHAPTER XVII

STREET-LIGHTING PRACTICE

In this chapter will be discussed some of the equipment and systems which are proving satisfactory and effective in lighting different classes of streets.

Illuminants.—The "luminous" or magnetite arc lamp and the type-C incandescent lamp are practically the only two illuminants used for street lighting. The magnetite lamp equipped with diffusing globes is used in lighting some of the most important

FIG. 217.—Pendant type luminous arc lamp with diffusing glass globe.

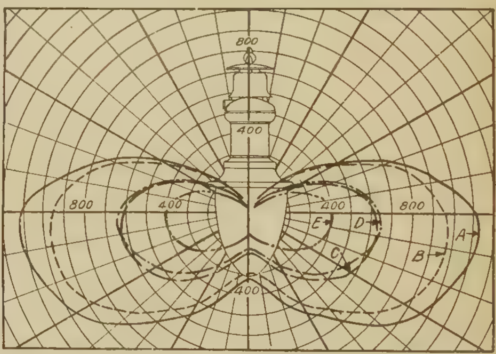


FIG. 218.—Initial distribution of candle-power in a vertical plane of the unit shown in Fig. 217.

and distinctive streets of many cities. The type-C lamp, being available in a wide range of sizes (600 to 25,000 lumens), is used for all classes of street lighting.

The *magnetite arc* lamp is economical and reliable in operation. It is made in two types, one for pendent lighting and one for ornamental or "white-way" lighting. It can be equipped with clear or diffusing glassware or with a prismatic refractor. Both long-life and high-efficiency electrodes are available, which, when operated at various currents (see Table 42), give a considerable range of candle-power values to this unit.

TABLE 42

Data on Direct-current Series Luminous Arc Lamps

Pendent type		Ornamental type	
Amperes	Watts	Amperes	Watts
4	310	4	330
5	388	5	403
6.6	510	6.6	532

Data for the pendent-type lamp are given in Fig. 218, and data for the ornamental-type lamp may be found in Fig. 220. These candle-power curves refer to lamps supplied with current and equipped with electrodes as follows:

A: 6.6-amp. long-life electrode with medium-density diffusing globe.

B: 5-amp. high-efficiency electrode with medium-density diffusng globe.

C: 5-amp. long-life electrode with light-density diffusing globe.

D: 4-amp. high-efficiency electrode with light-density diffusing globe.

E: 4-amp. long-life electrode with light-density diffusing globe.

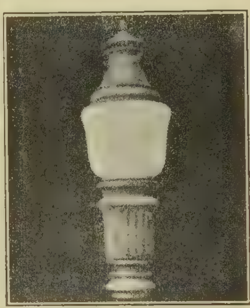


FIG. 219.—Ornamental type luminous arc lamp with diffusing glass globe.

The *type-C lamp* can be equipped with a variety of accessories suitable for all types of outdoor lighting from the rural highway to the ornamental systems in business districts. Various equipments of glassware and reflectors, together with a wide range of candle-power sizes, insure a flexibility which adapts this lamp to almost every condition to be met in street-lighting service.

The typical life curves for this lamp on series constant-current circuits are shown in Fig. 221, the increase in lumens being due to the increase in filament resistance during the life of the lamp.

The typical construction of the pendent unit is shown in Fig. 222, which is self-explanatory. Another construction is shown in Fig. 223, in which the location of the film cut-out is shown together with the receptacle clips and reinforcing springs which short-circuit the lamp when the socket is removed. Figure 224 shows

a magazine film cut-out being inserted in the clips. This magazine film cut-out is in the form of a roll which can be pulled along between the clips as new films are needed.

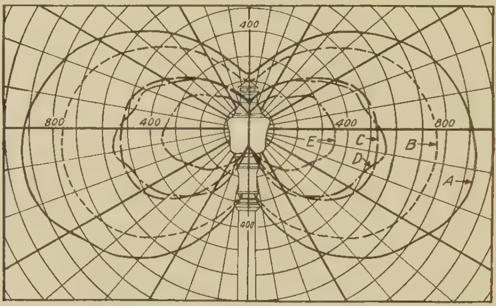


FIG. 220.—Initial distribution of candle-power in a vertical plane of the unit shown in Fig. 219.

The large lamps are more efficient when operated at 15 or 20 amp. than at lower current values. Since nearly all series alternating constant-current circuits are either 6.6 or 7.5 amp., individual autotransformers may be used for each lamp to supply

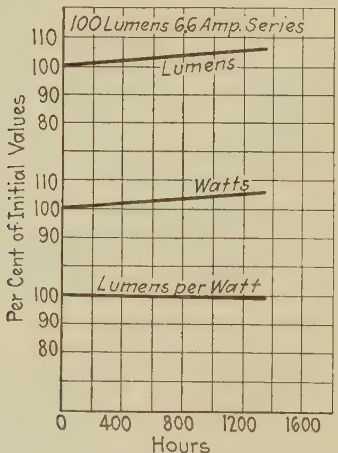


FIG 221.—Life performance of certain sizes of incandescent lamps for street lighting.

15 amp. for the 400-c.-p. and 20 amp. for the 600- and 1,000-c.-p. lamps. This device is mounted directly under the hood, as will be seen in Fig. 222. Its efficiency is 94 to 95 per cent, with a power factor of 99.5 per cent.

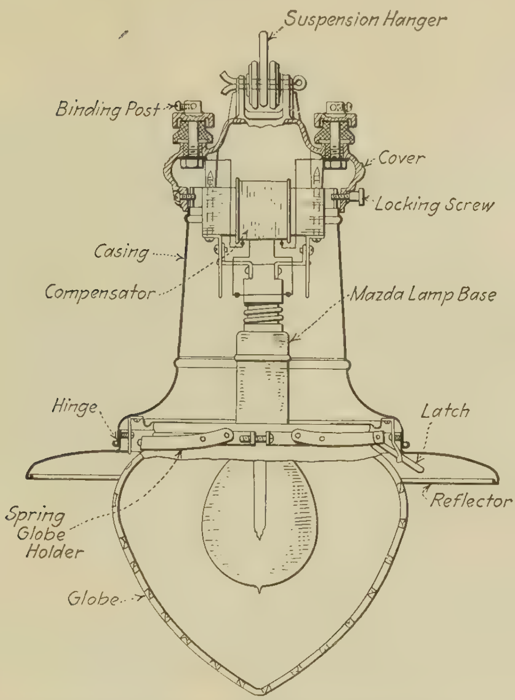


FIG. 222.—Construction of the pendant lighting unit for type C lamps.

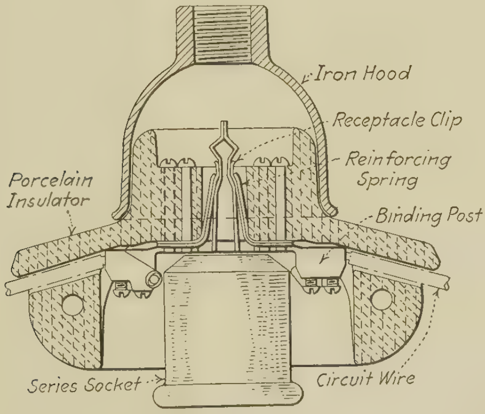


FIG. 223.—Cross section of hood and insulator for series bracket showing external wiring.

Figures 225 and 227 show the pendant and ornamental units for lamps of 250 to 1,000 c.p. The candle-power curves for these units are shown in Figs. 226 and 228 respectively.

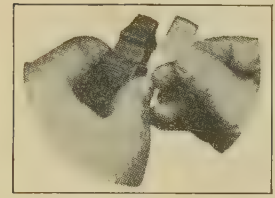


Fig. 224.—Magazine film cutout being inserted in the clips.

Fig. 225.—Novalux pendant unit with diffusing glass globe reflector used with 250-, 400-, 600- or 1,000-c-p. Mazda series lamp.

The Classes of Streets.—In considering the lighting, streets may properly be classed as follows: primary, secondary, and outlying business streets, streets of wholesale and manufacturing

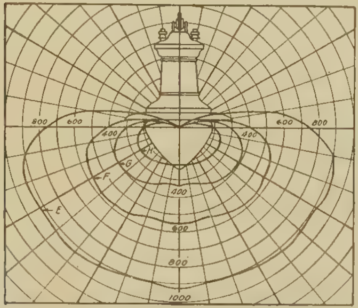


Fig. 226.—Initial distribution of candle-power in a vertical plane of the unit shown in Fig. 225.

Fig. 227.—Novalux ornamental unit with diffusing glass globe used with 400-, 600- or 1,000-c-p. Mazda series lamp.

districts, thoroughfares, residential streets, boulevards, parks, outlying-district and side streets, and highways.

The recommended standards for these various classes as regards intensity of illumination, mounting height, and spacing are given in Table 43.

The equipment of the lighting units should meet the requirements of the service as indicated in the preceding chapter. Obviously, the same type of reflector or glassware will prove

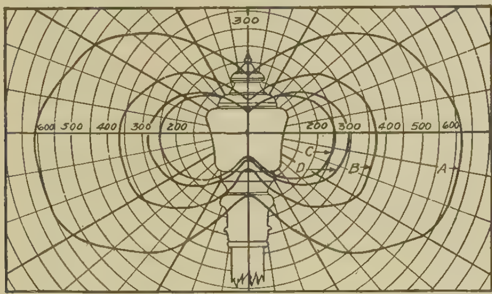


Fig. 228.—Initial distribution of candle-power in a vertical plane of the unit shown in Fig. 227. Curves, *A*, *B*, *C*, medium density, *D*, light density glass.

satisfactory for different classes of streets. Some of the different systems of street lighting will be discussed on the following pages.

Table 43

Recommended Standards for Street Lighting

	Class of street	Candle-power per unit	Mounting height, feet	Spacing, feet	Lamp lumens per linear foot of street
Range of lower limits. .	Primary business	600–1000	14–18	60–100	100– 330
Range of upper limits. .	. . . .	2500–5000	25	150	250–1000
Range of lower limits. .	Secondary business	600–1000	14–15	80–100	50– 150
Range of upper limits. .	. . . .	1000–2500	16–25	125	160– 500
Range of lower limits. .	Outlying business	250	12	60– 80	20– 125
Range of upper limits. .	. . . .	600	16	80–125	100– 200
Range of lower limits. .	Wholesale and manufacturing district	250– 400	20	125–150	20– 50
Range of upper limits. .	. . . .	1000–1500	25–30	250–300	50– 100
Range of lower limits. .	Thoroughfares	250– 400	15–20	75–150	10– 100
Range of upper limits. .	. . . .	600–1500	25–30	200–300	30– 125
Range of lower limits. .	Residential	100– 250	10–14	100–150	6– 40
Range of upper limits. .	. . . .	600	20–25	250–350	8– 50
Range of lower limits. .	Boulevards	250– 400	12–15	100–125	10– 60
Range of upper limits. .	. . . .	600–1000	20–25	200–300	30– 80
Range of lower limits. .	Parks	250	12–14	100–125	10– 40
Range of upper limits. .	. . . .	600–1000	20–25	200–300	30– 50
Range of lower limits. .	Outlying districts, alleys, and side streets	100	14–15	100–200	2.5– 10
Range of upper limits. .	. . . .	250– 600	18–20	250–400	5– 50
Range of lower limits. .	Highways	250	25–30	250–300	4– 8
Range of upper limits. .	. . . .	400	35	400–600	8– 12.5

Primary Business Streets—Intensive. *"White-way" Installations.*—Electric lighting on business streets had its inception in 1906 on Broadway, Los Angeles, in the form of a cluster globe system. The illumination from these original carbon lamps differed greatly both in intensity and in quality from the modern conception of a white-way. Similar systems were installed in St. Paul and many other cities. During the next 10 years remarkable progress was made and the white-way idea spread to practically every city and town of importance in the country. Cluster standards were largely superseded by single units using high-power incandescent and luminous arc lamps.

The Exposition in 1915 stimulated an interest in "light" that bore fruit first in the intensive illumination of Market Street, San Francisco, and then finally spread to include the entire retail business section of that city.

Such lighting is made possible by standards 18 or more ft. in height, carrying one, two, three, or more high-power luminous arc or incandescent units.

This system differed from previous white-way lighting in greatly increased illumination, relatively higher lamp standards, and greater initial installation, operation, and maintenance costs.

The system on Market Street consisted of trolley-pole standlards, each carrying three 6.6-amp. ornamental, luminous-arc lamps (Fig. 229). The standards were 32 ft. overall and were placed opposite at approximately 110-ft. intervals. The two side lights operated till midnight and were paid for by the Downtown Association. The center lamp operated all night at the city's expense.

All other retail business streets of San Francisco's downtown district had two-light luminous-arc standards, located in a staggered arrangement, with one standard to each 65 ft. of street. About 60 per cent of these operated till midnight and were paid for by the Association and the remainder operated all night at the expense of the city.

Salt Lake City installed a system similar to that of San Francisco. On Main Street, State Street, and Broadway, three-light luminous-arc lamp standards were used. These were 29 ft. overall and were spaced opposite at 100-ft. intervals. The property owners carried a large part of the expense.

In *Los Angeles*, an installation on Broadway consisted of two-light 6.6-amp. luminous-arc standards 27 ft. in height. Approxi-

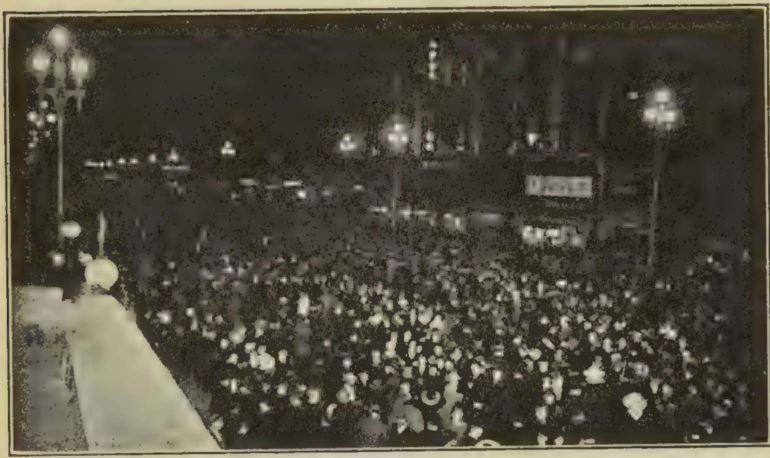


FIG. 229.—Carnival on Market Street, San Francisco, Cal., inaugurating "Path of Gold" lighting.

FIG. 230.—Main Street, Salt Lake City, Utah, intensively lighted by ornamental luminous arc lamps.

mately one-fourth of the lamps burned all night. The remainder were extinguished at midnight. The average spacing is 106 ft. and opposite.

For principal business streets in cities, the most widely favored method of lighting consists of single-light ornamental standards mounted at heights from 14 to 18 ft. and spaced opposite each other at distances of 80 to 120 ft. For very narrow streets the

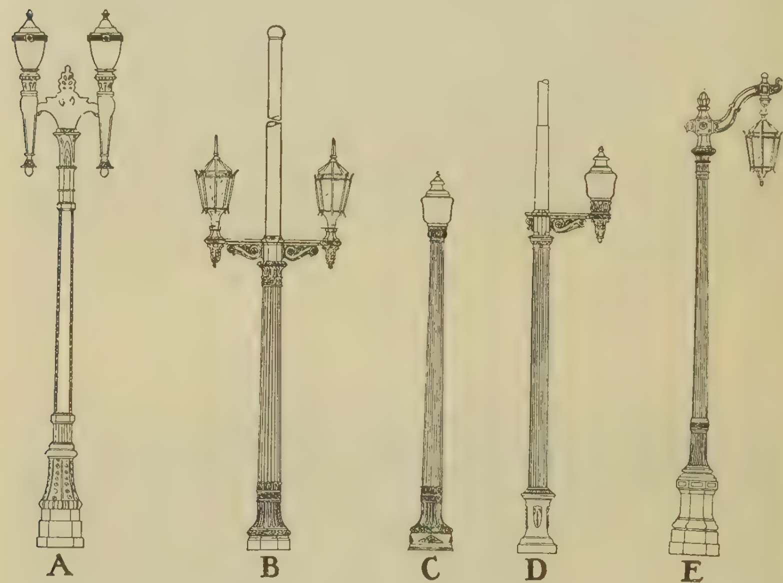


Fig. 231.—Methods of mounting White Way luminaires. A, specially designed ornamental two-light standard with Novalux form 12 ornamental luminaire. B, trolley pole twin bracket type with Novalux form 18 ornamental lantern type luminaire. C, ornamental standard for single light with form 9 Novalux luminaire. D, single light ornamental bracket for trolley pole mounting with Novalux form 9 luminaire. E, ornamental mast arm mounting with Novalux form 19 ornamental lantern type luminaire.

lamps may be placed on one side only, or staggered at the same spacing. An important increase in efficiency is secured by lamps of 600, 1,000, 1,500, or 2,500 c.p. instead of the three-, four-, or five-light clusters using small lamps which were the vogue before the introduction of the high-powered, gas-filled incandescent lamp. Typical equipments of modern character are shown in Fig. 231. There is at present a noticeable tendency to depart from the use of the opal ball or globe, and to use instead a lantern structure, which by many is considered more pleasing in appearance. Cleveland was the first large city to adopt equipment of

this character and has something over 1,500 standards similar to Fig. 231 E using 1,000- and 1,500-c.-p. incandescent lamps. These lanterns are glazed with a rippled glass and are used with prismatic refractors which increase the amount of light delivered to the street by turning downward the light rays which in an ordinary opal globe are largely lost.

Instead of the single-lamp standards spaced relatively close together, some cities have adopted standards carrying two or even three high-power lamps mounted 20 to 30 ft. above the street and spaced 150 to 200 ft. apart. The resultant effective

FIG. 232.—Night view of a White Way in a large city (Newark, N. J., population 420,000) lighted by form 6 Novalux luminaires with 15,000-lumen Mazda C lamps on ornamental trolley pole brackets. Height, 22 ft.; spacing, 120 ft. on both sides of the street, opposite.

illumination is not greatly different from the more usual arrangement and the exceptionally high mountings minimize any possibility of glare from the lamps. On the other hand, there appears to be much weight on the side of those who contend that on business streets the surrounding brightness of buildings, show windows, etc. is such that there is no possibility of serious glare, even with the large lamp at the lower mounting of 15 to 18 ft., and that the desirable white-way effect is enhanced by lanterns at these heights spaced 80 or 90 ft. apart.

The demand for higher levels of illumination on business streets has led in some cities to the consideration of lamp standards carrying two or three 1,000- or 1,500-c.-p. lamps each and

spaced no more widely than previous single-lamp installations. It is quite possible that there will be an increased development of this tendency, especially in the larger cities where the crowds from evening business and amusements have become such that in many cities white-way systems which were installed quite largely as an ornamental or advertising feature are even now barely adequate from the standpoint of lighting for safety.

Fig. 233.—Euclid Avenue, Cleveland—White Way district.

The installation on Euclid Avenue in Cleveland consists of 1,500-c.-p. series Mazda lamps mounted in stippled glass-paneled lanterns with special refractors which deliver approximately twice as much downward as upward light. The overall height of the standards is 16 ft. and they are placed on both sides of the street about 85 ft. apart.

The installation on South State Street, Chicago (Fig. 234), is representative of the comparatively successful results which may be assured at a relatively small installation expense. One thousand-watt multiple incandescent lamps in trolley-pole bracket fixtures are located 100 ft. apart on each side of the street.

At Saratoga Springs, N. Y., on Broadway, each standard has two "Duoflux" units. Each unit contains one 1,000-c.-p. and one 250-c.-p. series Mazda lamp. The large lamp in each unit is extinguished at midnight and the smaller one lighted. The change is accomplished through a relay, only one lighting circuit

Fig. 234.—State Street, looking south, Chicago, Ill., lighted by Novalux stippled glass globe units containing 1,000-watt multiple Mazda C lamps.

being necessary. This system should become an important factor in intensive street lighting. The design of the unit with its two lamps is shown in Fig. 235.

A lighting installation of interest is the "Relighting of Atlantic City's Boardwalk" (Figs. 236 and 237).[1] The old system consisted of two rows of standards mounted along the railings and spaced about 65 ft. apart. Each standard had a 150-watt, type-C lamp enclosed in a diffusing globe at a height of 19½ ft. and a cluster of four 100-watt type-C lamps in diffusing globes mounted on brackets at a height of 12½ ft.

A system was desired which could produce a high intensity on the walk on special occasions and during the evenings, when practically the entire population turns out *en masse*. A system

[1] *Gen. Elec. Rev.*, vol. 27, p. 803.

for such a location should permit easy recognition of people and objects at some little distance and give the much desired effect of sparkle, vivacity, and prosperity to the scene.

The asymmetric system of light distribution was adopted and the greater part of the light directed onto the boardwalk. The

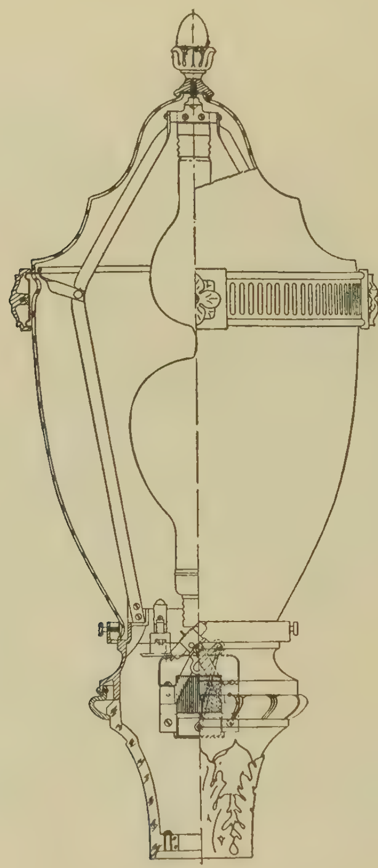


Fig. 235.—Sectional plan of the duoflux lighting unit.

existing standards were used, the brackets forming the cluster being removed. At the top of the pole is a rippled alabaster globe with a metal canopy. Within the globe are a 200-watt type-C lamp in a tip-up position and a 750-watt type-C lamp mounted tip-down. The former is 19 ft. 3 in., and the latter is 20 ft. 5 in. above the boardwalk.

Surrounding the larger lamp is an elliptical reflector arranged with its primary focus at the lamp filament, as shown in Fig. 238.

FIG. 236.—Comparison of old and new systems on Atlantic City Boardwalk.

Practically one-half of the upward light of the lamp is gathered by this reflector and concentrated at the conjugate focus several

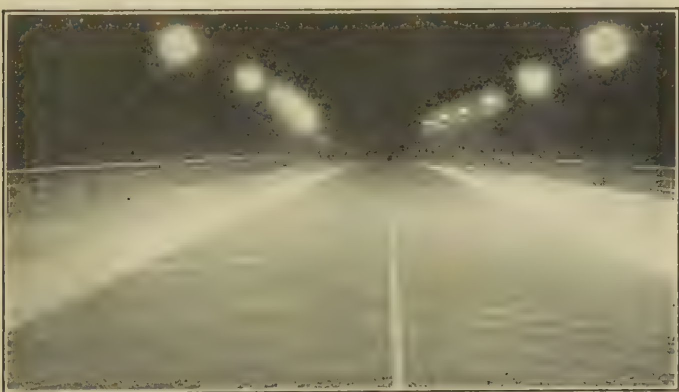


FIG. 237.—Appearance of the boardwalk at Atlantic City lighted by the new system.

inches below. Attached to an upright is a small plane reflector so placed that it intercepts the concentrated light from the elliptical reflector and redirects it toward the boardwalk.

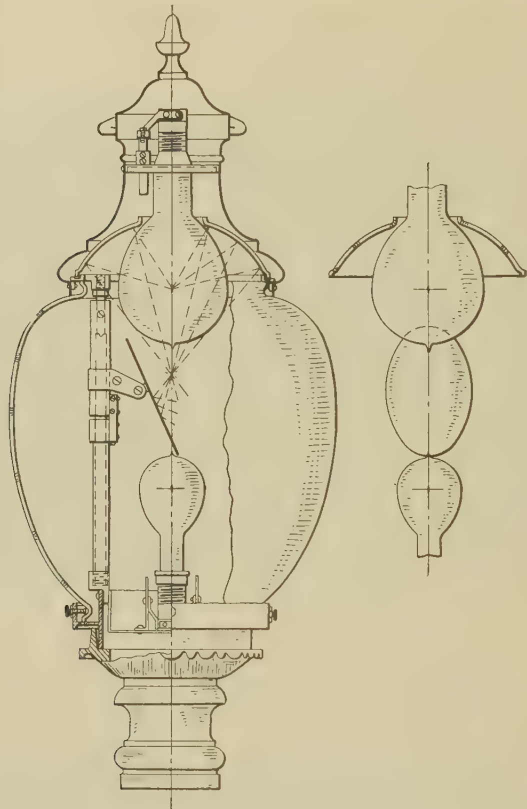


FIG. 238.—Sectional assembly of the ornamental Novalux unit with ellipsoidal asymmetric target reflector.

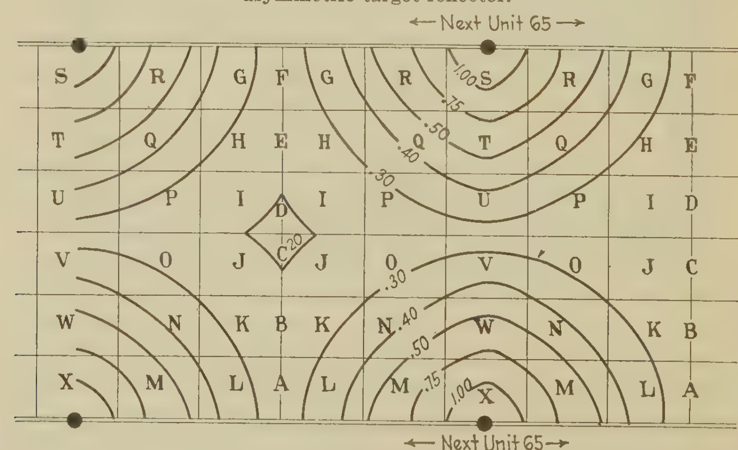


FIG. 239.—Isocandle curves of illumination by old system on boardwalk using all lamps on both sides. (See Table 1.)

The lamps are wired to separate circuits so that either or both may be used giving three intensities of illumination. Ordinarily, the 750-watt lamps burns from sunset until 1:00 a.m. and the 200-watt lamps from 1:00 a.m. until sunrise. It is obvious that by having the circuits on opposite sides of the walk separate, other intensities of illumination may be obtained, either by operating different sets of lamps on opposite sides or by extinguishing those on one side.

TABLE 44

Foot-candle Intensities

Both sides lighted	Old system	New system	Ratio of new to old
Average over whole area	0.38	1.57	4.1
Average in line of standards across boardwalk	0.70	2.40	3.4
Average midway between standards across boardwalk	0.23	0.99	4.4
Ratio $\frac{\text{minimum}}{\text{maximum}}$ on line of standards across boardwalk	0.32	0.66	
Ratio $\frac{\text{minimum}}{\text{maximum}}$ midway between standards across boardwalk	0.73	0.96	
Ratio $\frac{\text{lowest reading}}{\text{highest reading}}$	0.17	0.31	
Total wattage per standard	550	950	1.72
One side only lighted			
Average over whole area	0.19	0.83	4.4
Average in line of standards across boardwalk	0.33	1.16	3.5
Average midway between standards across boardwalk	0.10	0.53	5.3
Ratio $\frac{\text{minimum}}{\text{maximum}}$ on line of standards across boardwalk	0.03	0.13	
Ratio $\frac{\text{minimum}}{\text{maximum}}$ midway between standards across boardwalk	0.10	0.26	
Ratio $\frac{\text{lowest reading}}{\text{highest reading}}$	0.02	0.13	

Illumination tests were run on both the old and the new installations. A summary of the results is given in Table 44. The resulting illumination on different parts of the boardwalk is shown by the equilux lines of Fig. 240. Both the table and the curves in Fig. 240 show the effect of the use of the two reflectors, both as to efficiency and the distribution of the light.

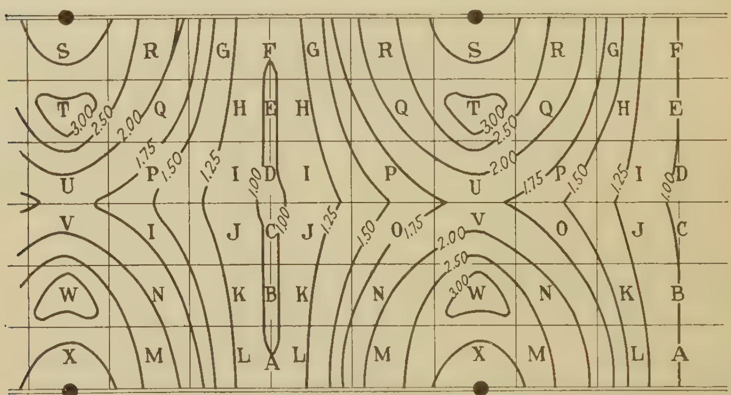


FIG. 240.—Illumination by new system on boardwalk using all lamps on both sides. (See Table 2.)

Thoroughfares.—The thoroughfares leading out from the business section have developed severe requirements for lighting under the new conditions of transportation. These streets carry high-speed traffic; a large percentage of street accidents occur in them, particularly at night in those cases where a proper provision for lighting has not yet been made. In some instances it is found practical to extend the high-intensity lighting of the business district to include these streets. This usually involves a greater expenditure than is permissible, however, and in any event the light-colored building surroundings characteristic of the business section are lacking in most of these thoroughfares. For this reason as well as because of the wider spacing, it is desirable to use a greater mounting height for the lamps in order to reduce the effect of glare. A fair provision for thoroughfares outside the business district is an arrangement of lamps of 600, 1,000, or 1,500 c.p. spaced from 150 to 250 ft. apart, or, at a maximum, 300 ft. If the street is very wide it may be necessary to consider each side as a separate street and provide lighting

accordingly. The mounting height should be 20 or preferably 25 ft., in order to remove the bright light sources farther from the line of vision, and also in order to obtain a better spread of illumination.

Residence Streets.—Where residence streets carry a large amount of through traffic they are, in effect, thoroughfares and should be lighted as such. In every city, however, a large percentage of street mileage is not used for through travel and, therefore, not subject to a large amount of high-speed traffic. Even in these streets, however, sufficient illumination must be provided to enable the discernment of objects and of obstructions

Fig. 241.—Lincoln Park Boulevard, entrance to park (Chicago).

on the pavement by one traveling at a moderate rate of speed. Illumination for sidewalks must also be provided which is adequate for comfortable walking and which does not leave such dark shadows behind tree trunks as might serve as possible hiding places for footpads. Residence streets are quite commonly well lined with trees; hence, unless the lamps are suspended over the center of the street, it is often necessary, in order to avoid a large loss of light, to use somewhat lower mounting heights than would be desirable on streets without trees. However, in view of the lower candle power of the lamps commonly used (250 c.p.), they may be placed as low as 15 ft. above the street without undue glare, provided the light is properly diffused and directed. When larger lamps are used and at wider spacings, heights of 18 or 20 ft. are considered better practice.

Lamp spacings on residence streets vary greatly. Where overhead wood-pole distribution is used and the appropriation

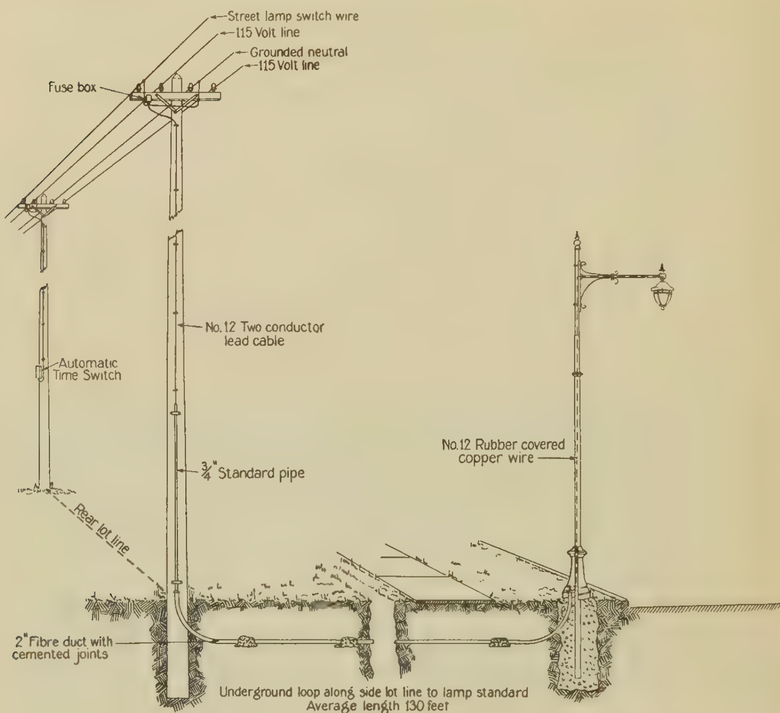


FIG. 242.—Pole line placed along rear lot line in residential section.

FIG. 243.—Thoroughfare lighting—East Cleveland. Residence streets have similar system with lines coming out from rear lot lines.

allowance is limited, spacings of 300 ft. may be used to give fair lighting, provided there are no trees to obstruct the spread of light. On the other hand, spacings of 100 ft. or even less are not uncommon for underground distribution supplying low-mounted ornamental units. Unless the interference from trees is excessive, spacings of 150 to 200 ft. are found satisfactory. The lamps are customarily staggered to reduce tree-trunk shadows.

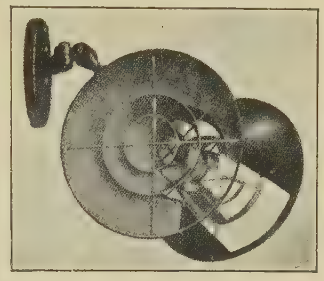


Fig. 244.—Highway lighting unit, showing the nest of parabolic reflectors on the near side and the flexible method of mounting the unit.

Highway Lighting.—*The highway lighting unit* involves several new features. This unit consists of six fire-enameled steel parabolic reflectors of three sizes, each set of three having a common axis and common focus and located on opposite sides of the lamp (see Fig. 244). The closed ends of the reflectors are removed and a rectangular opening is cut in the lower part of them. With this arrangement much of the light is redirected up and down the road. Very little goes to the sides or in an upward direction.

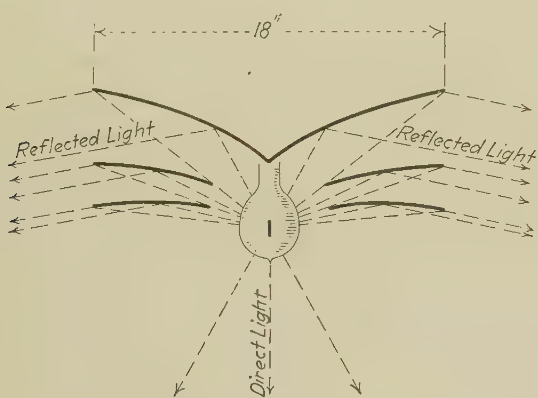


Fig. 245.—Diagram showing the paths of the reflected light and direct light from Novalux highway lighting unit.

The value of this can best be appreciated by referring to the photometric curve in Fig. 247, which shows more than 4,000 c.p. from each end of the unit, with a 250-c.-p. 155-watt lamp. Thus, most of the upward and side light is available for illuminat-

ing the roadway. Furthermore, the narrow intense beam of light will illuminate the road for a great distance in both directions. Excellent results can be obtained by placing the units 300 ft. apart, using 250-c.-p. lamps, and very good results can be

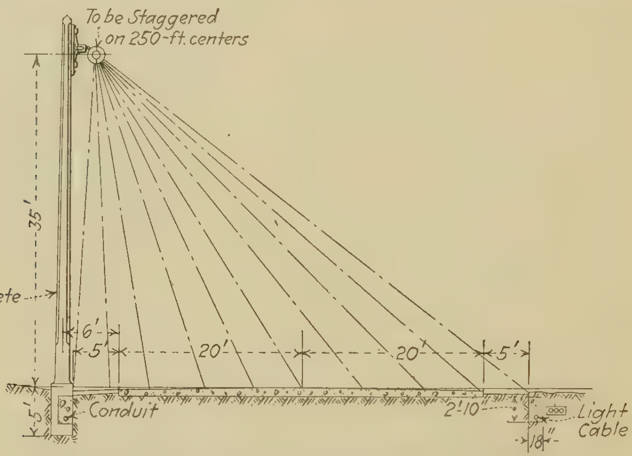


FIG. 246.—Typical section across Lincoln Highway.

obtained with spacings up to 600 ft. This unit makes economically possible the satisfactory lighting of highways which must otherwise remain unlighted, or at least insufficiently lighted.

The fixture has an adjustable bracket, so that the rectangular openings may be turned toward the road surface (Fig. 244) and

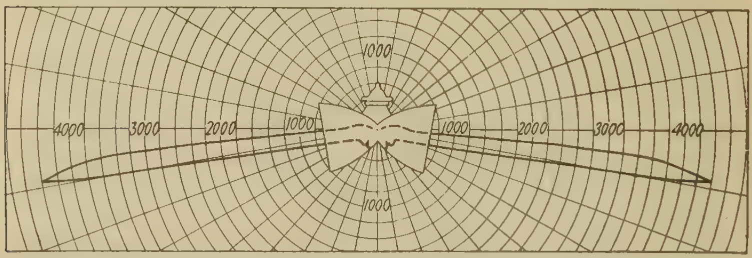


FIG. 247.—Preliminary photometric distribution curve of light from a 250-c-p., 4-amp. highway lighting unit operated at 2,500 lumens.

the unit tipped when installed on hills or at curves. This unit should be mounted 30 to 35 ft. above the road surface.

The first impression from the candle-power curve may be that there will be an enormous amount of glare, but this is not the

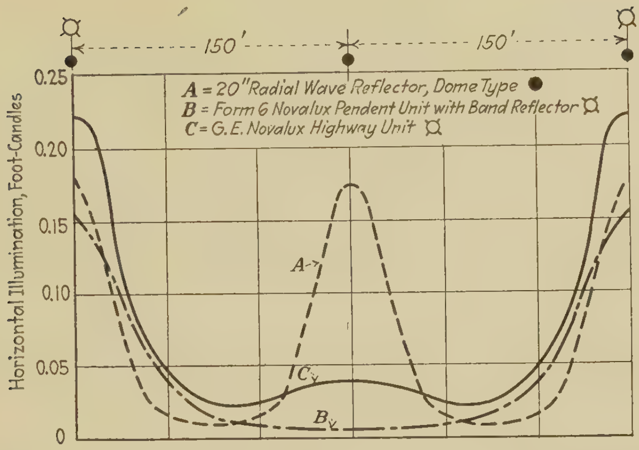


FIG. 248.—Comparative illumination with approximately equal wattage. Illumination is calculated along the center line of the road on its surface with "Mazda C" series lamps mounted 10 ft. from the center line. With system A a 100-c.-p. lamp mounted 20 ft. above the road is used every 150 ft.; with system B and C 250-c.-p. units mounted 30 ft. are used every 300 ft. The ratio of minimum illumination to maximum is 0.062 with system A, 0.045 with B and 0.11 with C.

FIG. 249.

case, as the illuminating surfaces of the reflector replace the brightness of the lamp and the effect is more like that of a diffusing globe. As Fig. 249 shows, the roadway is lighted and objects will be seen in silhouette.

Depreciation of Outdoor Lighting Equipment.—The depreciation of outdoor lighting equipment was investigated in Cleveland at the same time as the investigation of indoor equipment described in Chap. XI. Seven units were operated on the roof of a factory warehouse. They were lighted two 2-hr. periods each day, for 120 days.

The following table gives a description of the equipment included and the relative depreciation measured at the end of the test period.

TABLE 45

Luminaire	Depreciation	
	Relative	Actual
A. Nested parabolic enameled-steel reflectors	100	41.2
B. Flat enameled-steel reflector, bowl refractor, closed bottom	85	34.9
C. Ventilated fixture dome refractor, clear rippled globe, hole in bottom	83	34.2
D. Dome refractor without globe	69	28.3
E. Light opal eight-paneled hinged-top lantern, dome refractor	68	27.9
F. Dust-tight fixture one-piece cast top, felt globe gasket, dome refractor and light rippled globe—no hole in the bottom	58	23.8
G. Radial fluted enameled-steel reflector	37	15.3

The test results on units C and F demonstrate the usefulness of closed dust-tight luminaires in reducing the depreciation due to the collection of dust, as compared with units having globes with holes in the bottom. Incidentally, the hole represents an extra cost, as it must be ground after the globe is blown, adding an extra operation in production. The hole also weakens the globe, increasing the breakage in handling and service.

Holes were necessary when globes were used on old arc-lighting equipment, to supply air circulation and ventilation to carry off

the fumes. Incandescent lamps require no such circulation of air and many thousands of units in street-lighting installations equipped with globes having bottom holes would be more efficient if a change was made to globes without holes.

Maintenance.—In most cases all that is required to avoid waste of light is a cleaning of the lighting equipment at regular intervals of approximately 1 month (oftener in very dirty locations and less often in exceptionally clean places) and a prompt renewal of burned-out or obviously defective lamps. Arc lamps giving off fumes and products of combustion should be cleaned each time new electrodes are installed.

CHAPTER XVIII

THE PROJECTION OF LIGHT

This chapter is devoted to the study of the fundamental principles of various projection devices now in use, such as the stereopticon, motion-picture machine, headlights, searchlights, and floodlights.

In apparatus of this nature the light is concentrated into beams or cones of light of high intensity and of comparatively small cross-sectional area.

Parabolic Reflectors.—The most common direct-reflecting device is the parabolic reflector. It has a wide use in light-projection units. It is usually made of spun or drawn metal with a highly polished surface and has such a shape that all reflected light originating at its focal point will be directed parallel to its principal axis. If a point source were possible and the reflecting surface of the parabola could be made perfect, then all reflected rays would be parallel, and the diameter of the beam would be the same as the diameter of the reflector, as shown in the lower half of Fig. 250. In actual practice it is impossible to secure a point source of light, and the parabola, no matter how carefully constructed, does not have a perfect surface. What really happens is shown in the top half of the figure. The image of the filament is reflected from P in the form of a cone in the direction of X, which is parallel to AA, the principal axis. In commercial practice a very concentrated light source is used, and the resultant beam is made up of cones of light, the rays of which are *approximately* parallel. The beam is slightly divergent. The candle power of this beam will be thousands of times the candle power of the direct rays of the lamp which is used to produce

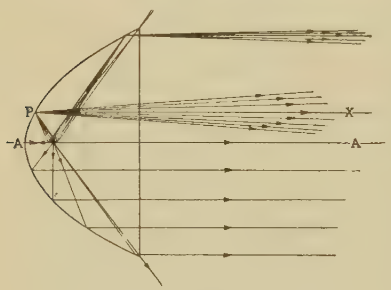


FIG. 250.—Principle of the parabolic reflector.

the beam. This increase is due solely to the fact that the light given off in the direction of the reflector is collected and condensed to form the beam. If the light source is not at the focal point, the rays will spread as shown in Figs. 251 and 252.

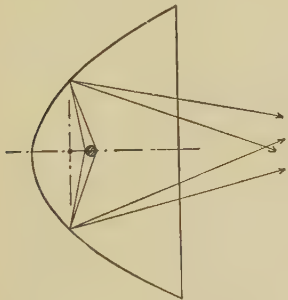


FIG. 251.—Lamp located ahead of local point.

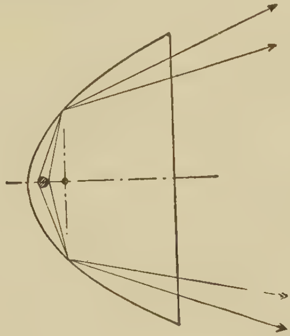


FIG. 252.—Lamp located behind the local point.

Spherical Mirrors.—Another form of reflecting device common in projection work is the spherical mirror. It is usually made of glass in the form of a section of a sphere. The outside surface is silvered to form the reflecting surface. The focal length of the mirror is the radius of the outside curvature (Fig. 253). In the sketch the light rays from a point source are reflected back on themselves from a perfect reflector, thus nearly doubling

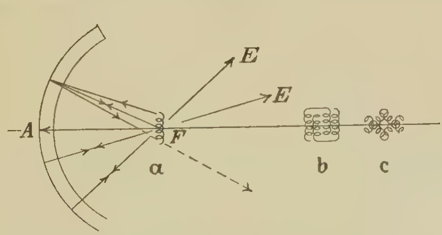


FIG. 253.—The spherical mirror.

the amount of light in the directions EE. In practice, as shown in the upper half of the sketch and in the cross-section taken at the focal point, the image of the total filament is reflected, and thus inverted, back on itself. It is customary so to adjust the filament that the image is slightly displaced, so that the effect is a nearly solid light source, as shown in b. The effect of a V-type filament is shown in c, the image being the lighter portion, and inverted.

Mangin Mirrors.—The third form of reflecting device in common use is the Mangin mirror. The Mangin mirror is made of glass, the inner surface of which is a section of a sphere of a certain radius. The outer surface is also a section of a sphere, but has a radius of curvature differing materially from that of the inner surface. This outer surface is covered with a reflecting material. In this type of mirror the refraction of the glass is taken into consideration and the curvature of the outer surface is adjusted to the index of refraction of the glass which is used. The Mangin mirror is usually shallow in design, thus giving a long focal length, which causes a more sharply defined beam than that secured from a parabola. The accuracy with which it can be made makes it particularly adjustable to searchlights, and the long focal length makes it suitable for operation with flame or arc-light sources as well as with incandescent lamps.

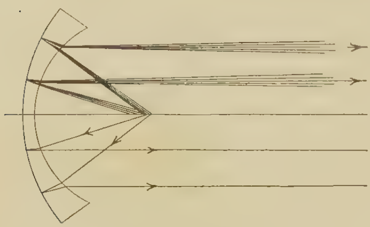


Fig. 254.—The Mangin mirror.

In the sketch (Fig. 254), as in the two preceding ones, the principal axis divides the mirror into the actual and the theoretical diagrams. It will be noticed that in the upper half the cone of light is of less diameter than that of the parabola, due to the longer focal length, and, therefore, the beam will be of narrower spread.

Referring to the parabolic reflector and the Mangin mirror, it will be noted that the light is reflected in parallel rays. The spherical mirror reflects the light back on the source if properly adjusted. Hence, in order to produce a beam of light, additional equipment is necessary. This usually takes the form of lenses, of which there are several types.

Lenses.—To control further or to direct the rays in the beam of light coming from the light source and the reflector, lenses are necessary. In the stereopticon and moving-picture machine lenses are necessary to gather or condense the light rays, thereby increasing the intensity of the beam. They are also necessary to overcome the optical defects known as "spherical" and "chromatic" aberration.

Spherical aberration is caused by unequal diffraction of the light rays in different zones of a lens. This causes the rays from

some zones to cross the principal axis of the lens before those from other zones, and a blurred image results (Fig. 255). To overcome this aberration a concave lens is usually combined with the convex lens and the set balanced so that all the parallel rays are brought to one focus.

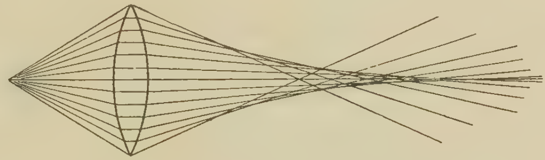


FIG. 255.—Illustrating spherical aberration.

Another phenomena of refraction is *chromatic aberration*, or the separation of images produced by the different wave lengths of which light is composed; that is, the image produced by the red end of the spectrum will have a focal point at a different place on the principal axis than the image formed by the violet end (Fig. 256). This defect is rectified by the combination of lenses of different qualities of glass, such as crown and flint. Thus, by combining a convex crown-glass lens with a concave flint-glass lens, it is possible to get a combination nearly free from both chromatic and spherical aberration.

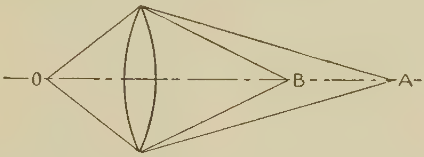


FIG. 256.—Illustrating chromatic aberration.

In some types of headlights, signal lamps, etc., lenses are used in conjunction with the spherical mirror for securing a more concentrated beam of light. The principle upon which many of these lenses are constructed is that of the Fresnel reflecting rings illustrated in Fig. 257, the commercial types being molded with the concentric prisms projecting, as will be seen in later illustrations.

Several types of condenser lenses are in use. They form such a vital part of the projection that the more important will be described, starting with the plano-convex lenses.

The *plano-convex lenses* of the type used for moving-picture work are shown in Fig. 258. One side of each of these is perfectly

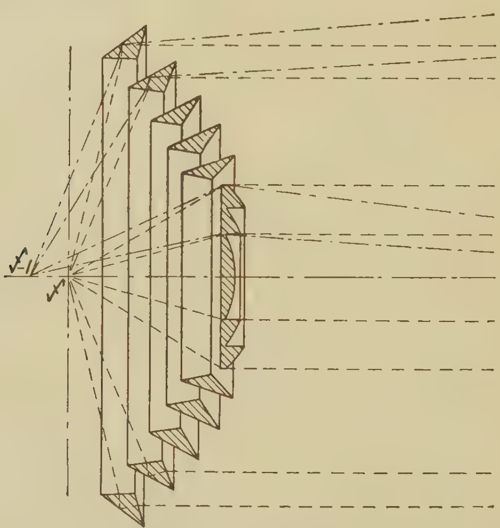


FIG. 257.—Diagram of a system of totally reflecting rings originated by Fresnel.

plane, while the other side is ground to the shape of a portion of the surface of a sphere. Rays of light from the lamp strike the surface of the lens and are refracted or condensed in the manner shown.

The *corrugated condenser lens* is an attempt to combine in one lens the advantages of the two-

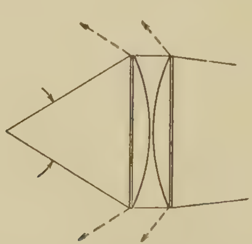


FIG. 258.—Plano-convex lenses showing light lost by reflection.

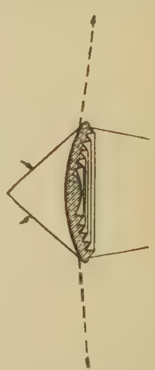


FIG. 259.—Corrugated lens showing light lost by reflection.

lens system and at the same time eliminate the disadvantages of the spherical and chromatic aberration to which all thick lenses are subject. The construction is shown in Fig. 259, it being a

modified Fresnel lens. This is similar to the thick double-convex lens, with the difference that a large part of the glass, especially near the center of the lens, has been eliminated. As will be seen from the illustration, the corrugated lens consists of a small bull's-eye in the center, surrounded by a series of concentric prisms.

It is obvious that the length of the path of the rays through the glass is less in this lens; therefore there is less absorption of light. Also, since the light strikes only one surface in this lens, there will be less loss from reflected light than in the two-lens condenser.

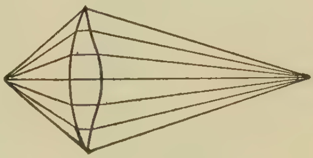


FIG. 260.—The aspheric condenser lens.

The *aspheric lens* has been designed to eliminate the errors due to spherical aberration. As previously shown, the light which passes through the outer zones of a double-convex lens are refracted too much in comparison with light which passes nearer the center. This type of lens is shown in Fig. 260. The curvature of one surface is such that the lens is flattened near the edge by just the proper amount to compensate for spherical aberration.

The *parabolic condenser system* comprises two lenses ground with special parabolic curves designed to control the light more accurately and efficiently than can be done with the common spherical-surface lens.

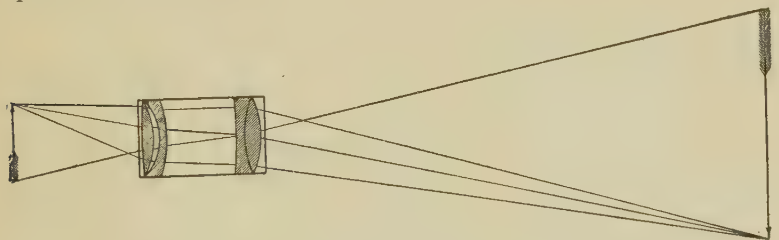


FIG. 261.—The projection of an image with commercial type lens.

The *objective* or *projection lens* of the stereopticon receives the light rays after they have passed through the aperture and the film or slide, and forms a greatly enlarged image of the picture on the screen. A simple double-convex lens at this point, as in the condenser lens, cannot eliminate spherical and chromatic aberration. It is to overcome these defects that the more complex type of lens shown in Fig. 261 has been designed, represent-

ing the actual construction of the typical objective lens in commercial use today. Certain of the individual lenses in the objective are made of different kinds of glass (crown and flint), as previously explained. The surfaces of the individual lenses are carefully designed and carefully ground in order to give a clear, sharp picture on the screen.

The Stereopticon.—The component parts of a stereopticon are, first, the light source, usually a stereopticon lamp and a mirror placed behind the lamp; a condensing unit, composed of one or more lenses; an accurately ground objective lens; the housing, slide carrier, etc.

The mirror intercepts the light coming in its direction and redirects it toward the condenser. The condenser refracts the

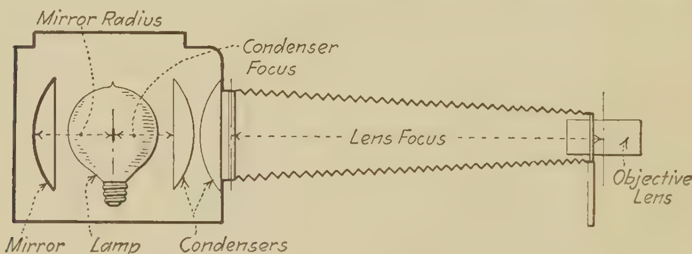


FIG. 262.—The principal parts of a stereopticon lantern: mirror, lamp, condenser, slide and slide carrier, objective lens. Notice the housing which covers up the light source, and the bellows which encloses the light beam from the slide to the projection lens.

rays of light received from the lamp and mirror, so that, after passing through the slide, they will enter the objective lens.

The objective lens gathers the rays of light coming through the slide and projects them upon the screen. The location of parts and the plan of the stereopticon are shown in Fig. 262.

It is important to have all the elements accurately lined up on the optical axis. The light source is subject to variations and one lamp may vary somewhat from another. When a new lamp is inserted, it should be carefully focused. A method of determining the proper location of the light source, and one which is particularly valuable when dealing with an incandescent lamp, is as follows: Take a piece of black cardboard or similar material and hold it a couple inches in front of the objective lens. A distinct image of the filament will be seen in the circle of light thrown on this cardboard. The filament should be moved forward and back until it appears sharpest, and then moved up,

down, or to the side, till accurately centered in the spot. The mirror which is nearly always used with an incandescent lamp should now be adjusted by moving in the same manner as the lamp to secure the clearest image. Then the position of the image should be fixed so that the coils of the lamp filament and of the image will appear of the same size and located as shown in Fig. 263, F representing the filament and I the image. Figure

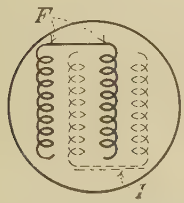


Fig. 263.—Showing the relative positions of the filament and the reflected image.

Fig. 264.—Lamp filament lighted with no mirror image.

Fig. 265.—Mirror images correctly located.

264 shows the appearance of the filament lighted, with no mirror image, while Fig. 265 shows the appearance with the image correctly located.

The Motion-picture Machine.—The optical system of this apparatus is similar to that of the stereopticon. The necessary elements are shown in Fig. 266. It will be seen that the condenser C collects the light from the lamp and mirror and redirects it to the aperture A, where the film is located. Not only is it

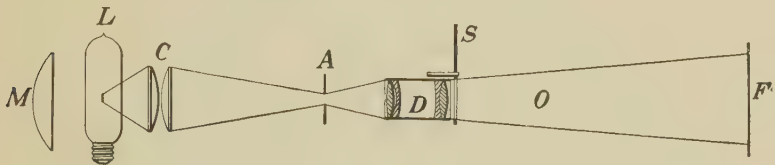


Fig. 266.—Complete optical system for projection with Mazda lamp.

necessary to have the largest amount of light strike the film, but this light should come in the proper direction to pass on through the objective lens D and to the screen.

The lens at D is of the complex type to overcome the defects due to spherical and chromatic aberration, and represents the actual construction of the typical objective lens.

The rotary shutter at S cuts off the light while the film is moving. The screen F receives the picture which is projected

by the optical system. The light that it reflects back to the eye is the only portion which enables the formation of a visual picture.

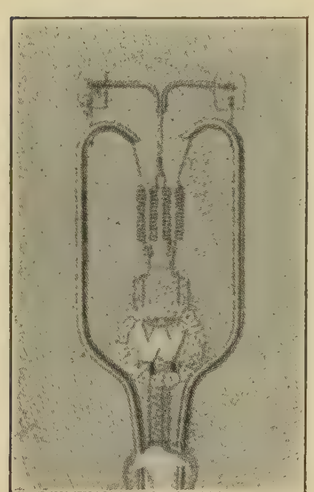


FIG. 267.—Construction of the stereopticon lamp.

Lamps.—In general, with screen sizes up to 12 by 16 ft. and projection distances up to 100 ft. the gas-filled incandescent lamp is feasible. One type of construction is shown in Fig. 267. The filament is concentrated and accurately located. The gas, about 80 per cent argon and 20 per cent nitrogen, makes it possible to operate the filament at a much higher temperature (3000°C.), thereby adding greatly to the efficiency of the unit. Motion-picture lamps are designed for a life of about 100 hr. The bulb, because of the high temperature, is made of special glass.

The Screen.—Screens may be classified according to their surfaces, as diffusing, metallic, or beaded. The light-reflecting properties of these three types of screens are shown in Fig. 268. The

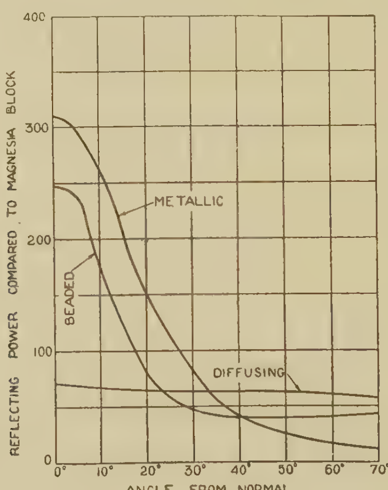


FIG. 268.—Distribution of reflected light from three types of motion picture screens.

diffusing screen, to which the flat-mat plaster surface is a common example, gives the picture practically the same bright-

ness from whatever angle it may be viewed. This type of screen is necessary in an auditorium which is wide in proportion to its length.

The metallic and beaded screens show semiregular reflection, and are desirable for a long, narrow house. The difference in

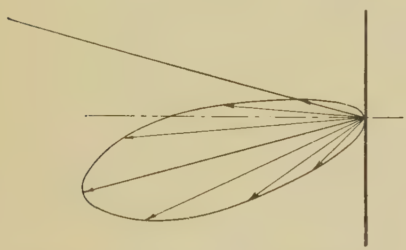


Fig. 269.—Distribution of reflected light from metallic screen.

Fig. 270.—Distribution of reflected light from beaded screen.

the reflecting properties of these two screens is shown in Figs. 269 and 270. In the beaded screen the light is reflected back in the general direction of the projected beam. When the house has a high projection booth, the type of screen and its location must be so planned that they will produce satisfactory picture brightness for the entire theater.

CHAPTER XIX

SEARCHLIGHTS, HEADLIGHTS, AND FLOODLIGHTS

Searchlights.—Searchlights have been used for military purposes for more than 50 years. They have proved an effective instrument of defense against night attack, for locating enemy ships, torpedoes, fortifications, airplanes, and for signaling purposes. They are also used extensively on commercial vessels for a variety of purposes.

The standard equipment consists of an accurately constructed parabolic mirror and a direct-current arc, although Mangin mirrors as well as incandescent lamps are also used in the smaller-size searchlight.

The discovery of the *high-intensity arc* about 1914 marked the beginning of a new era in the history of the searchlight. Whereas carbon electrodes of comparatively large side, operated at low-current density, were previously used, new electrodes of the flame type to operate at high-current density were developed.

The positive electrode of the 150-amp. arc will be described as illustrative of the type. Its diameter is 16 mm. and its core just half this in diameter. The core contains a large percentage of cerium fluoride. It is less dense and hard and is inserted in the shell with a minimum of clearance. The shell itself is carbon of high purity, formed under pressure, and is exceedingly hard. The electrode is brittle and requires care in handling.

The negative electrode is of pure carbon throughout and has a hard shell 11 mm. in diameter and a core 3 mm. in diameter. The function of this core is to keep the arc centered. The core burns below the end of the shell and the sharp edge of the hole in the shell forms a fixed taking-off point for the arc.

The positive electrode is rotated steadily at about 16 r.p.m. during operation. The negative electrode is not ordinarily rotated. After a few minutes' operation the salt-laden core of the positive has burned some 7 or 8 mm. from the end of the shell and the inner part of the shell itself has burned out, forming a crater 14 mm. across. This crater is uniform in size and form

throughout the life of the electrode. The rotation of the electrode makes the burning rate uniform around the shell and preserves the symmetry of the crater rim. This latter feature is vital to the successful operation of the arc.

With the high-current density used, the positive electrode is at a white heat. This high temperature drives off the fluorides which act as a conductor for the current. The gas within the crater has a brilliancy of 700 candles per square millimeter at the point of greatest crater depth, and as the gas is transparent the crater walls add some 135 candles per square millimeter, giving a total brilliancy of about 835 candles per square millimeter of projected area, or over six times the best brilliancy of pure carbon.

Glass Searchlight Mirrors.—Silvered glass makes a most durable reflector surface, since the glass protects the highly reflecting silver from corroding or getting scratched, tarnished, etc. Practice proves that a true parabolic reflector will not produce a beam of parallel rays: first, because a parallel beam results only when the source of light is a point; and, second, the thickness of the glass in front of the silver produces a refraction that interferes with the parallelism of the rays. This latter effect was shown in the Mangin mirror previously described. It has been found necessary to give the convex surface a curve somewhat different from a parabola so that the refraction produced combined with the effect resulting from the size of the source will cooperate to produce a parallel beam.

A glass has been produced that with proper annealing is very tough. It is remarkably free from stones, striae, bubbles, fisheyes, comets, stars, stone cracks, etc., and has a good color and a low-absorption coefficient. When the mirror is silvered and properly backed it withstands all ordinary strains due to heat, shell fire, and other causes.

As proper glass is an absolute necessity, great care is required in its manufacture. The ingredients must be of the proper quality and proportions. The temperature of the furnace and the length of time the melt is left in the furnace must be carefully attended to. The pouring and the annealing of the plate are important factors.

Glass which has passed inspection for the imperfections listed above, and has been tested for toughness and proper annealing, is ready for some fifteen steps in the manufacture of the mirror.

First comes the bending of the disk to the required form and again annealing it. The annealing should be carefully done and thoroughly tested, since upon this depends the toughness of the glass and the durability of the mirror. Polarized light may be used for testing the annealing.

The disk is then ground, smoothed, and polished and when a surface free from sleets, scratches, and surface flaws is produced the convex surface is silvered. The mirror should next be inspected and tested carefully for form of curve and for focus.

The *test for focus* consists in moving a beam of light 1 in. in diameter projected parallel to the axis of the mirror across the mirror perpendicular to the axis. The reflected beam should pass through a point which remains fixed. When this occurs, the mirror has no spherical aberration.

The reflection from the mirror of a screen, consisting of a series of lines so ruled as to form squares, is photographed. A regular series of lines will indicate that the mirror is uniform in thickness and free from irregularities caused by grinding.

The *night illumination test* consists in placing at the focal point of the mirror an intense source of light. If the mirror is of correct curvature the reflected rays will be parallel and will show uniform intensity on any given diameter. It will be free from zones and free from ghosts. These ghosts are cones of light outside the parallel beam and are caused by irregularities in the surface of the mirror.

In the tests of mirrors the optical qualities rather than the appearance of the mirror must be looked after. A bubble in the glass may look bad, but it is of little importance optically. A slight defect in the curvature may lessen the optical efficiency by a considerable amount and yet in no way interfere with the appearance of the mirror.

Metal Searchlight Mirrors.—The successful production of metal mirrors as large as 60 in. in diameter was one of the interesting war developments. A parabolic glass mirror was used for a form. The outside surface was used after having been carefully and accurately ground and polished. This surface was then thoroughly cleaned, after which it was silvered by the ordinary mirror-silvering process. It was then put in a silver-plating solution, where the silver was built up to several ten-thousandths of an inch. It was then put into a copper-plating bath and copper deposited on the silver until a thickness of about

0.03 in. was produced. After washing and drying, a coat of adhesive material was applied to the surface of the copper and allowed to dry. Then a backing in the form of a plastic coating was applied to a thickness of ½ in. When dry, the glass was removed and, if necessary, the silver surface cleaned. No polishing was necessary. To protect the silver surface from atmospheric conditions, a coat of lacquer was flowed on and allowed to dry in a dust-free room. The reflector so constructed

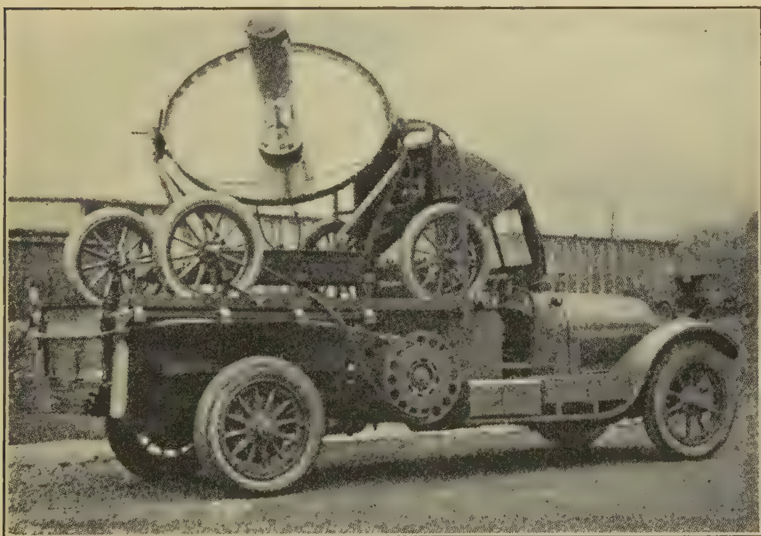


FIG. 271.—1918 model, 60-inch size, mobile searchlight equipment.

was further strengthened by the addition of a ribbed sheet-steel backing, making a durable piece of apparatus.

Tests of the losses due to diffusion and absorption of the front glass or door of searchlights showed a decrease of 25 per cent in the average intensity of the beam. This lead to the operation of searchlights without the front glass. The practice was successful and resulted in the development of the open-type unit.

Mobile power units combined with mobile searchlights were developed during the war. Notable among these was the G. E. Cadillac design. This unit employed a standard automobile engine and chassis (Fig. 271). The generator was placed concentric with the propeller shaft and was connected to it through

a grill. A standard Cadillac clutch and gear shift enabled the engine to be connected to either the generator or the automobile propellor shaft. The generator was of 105-volt, 20-kw. capacity. The unit carried a 60-in. open-type searchlight and 600 ft. of cable. Larger and smaller units were also developed.

The *intensities* of some of the searchlight beams, showing the progress made in the art and for the most part due to the development of the high-intensity electrodes, are shown in Fig. 272.

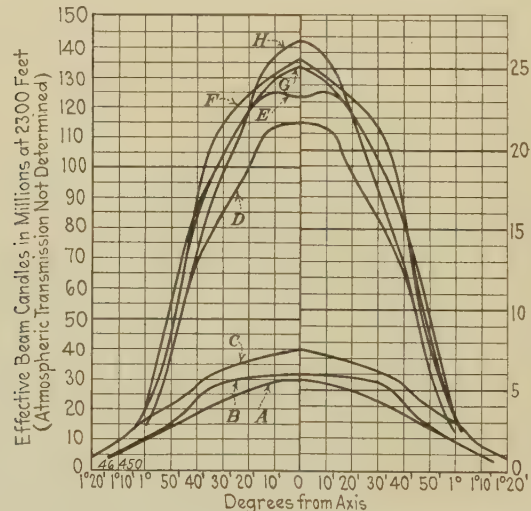


Fig. 272.—These curves of beam intensities illustrate the great improvement realized in efficiency through using a better designed and manufactured electrode.

Curves *A*, *B*, and *C* show the prewar intensities from 60-in. searchlights *A* referring to a 175-amp. lamp and *B* and *C* to a 200-amp. lamp. Curves *D* to *H* show results with five of the most promising electrodes developed during the war. These were operating at 200 amp. and 60 to 65 volts. The intensity of searchlight beams may be as high as 700,000,000 c.p. when operating under best conditions.

Many striking changes take place in the high-intensity beam when the crater is moved from or along the axis so as to remove it from the focal point. The results of photometric tests on a 36-in. searchlight at a distance of 2,300 ft. taken to learn just what influence the focusing of the arc had on the central beam intensity,

beam width, and total flux are shown in Figs. 273 and 274. Taking the focal length as the unit of measurement, it is found that a movement of 0.01 focal length away from the mirror lowers the central intensity 25 per cent. A movement of 0.02 focal length in the same direction results in a decrease of 58 per cent. When the crater is within 0.005 focal length (or 0.074 in.) the decrease is 5 per cent, and this may be considered

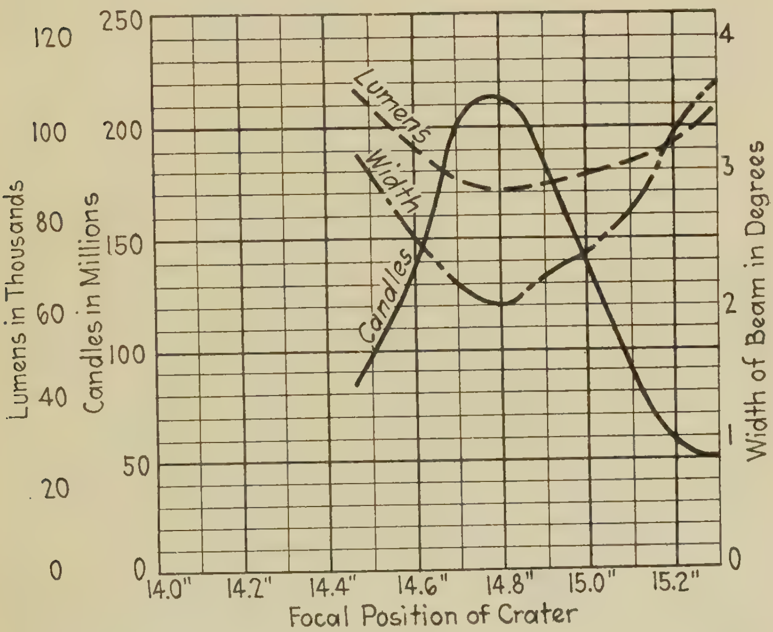


FIG. 273.—The dependence of central beam intensity, beam width, and beam lumens upon the focal positions of the crater is illustrated by these curves for a 36-in. mirror.

as the reasonable limits of adjustment for maintaining full central intensity.

A casual observer seeing the beam go through the changes illustrated in Fig. 274 would be greatly surprised if told the exact magnitude of the change he witnessed. The normal beam would seem to him to be of almost uniform intensity across its diameter even if thrown on a flat surface where the illumination can be readily viewed. The center would, of course, seem somewhat brighter than the edges but hardly in the ratio of 10 to 1.

(The attention of the reader is here called to Fechner's law of sensation in Chap. II.) The tendency here is for the eye to minimize the differences in illumination. From this observation one might attempt to reason that the beam *G* would give an illumination of great apparent uniformity. The casual observer, however, would not hesitate to pronounce the illumination a ring of light with a dark or black center. Here the eye exaggerates the differences of illumination. No reasonable explanation appears to have been found for this phenomenon. It has a bearing on searchlight practice in only one known way. A beam of light spread to cover a greater area should usually not be widened further once the dark center has appeared.

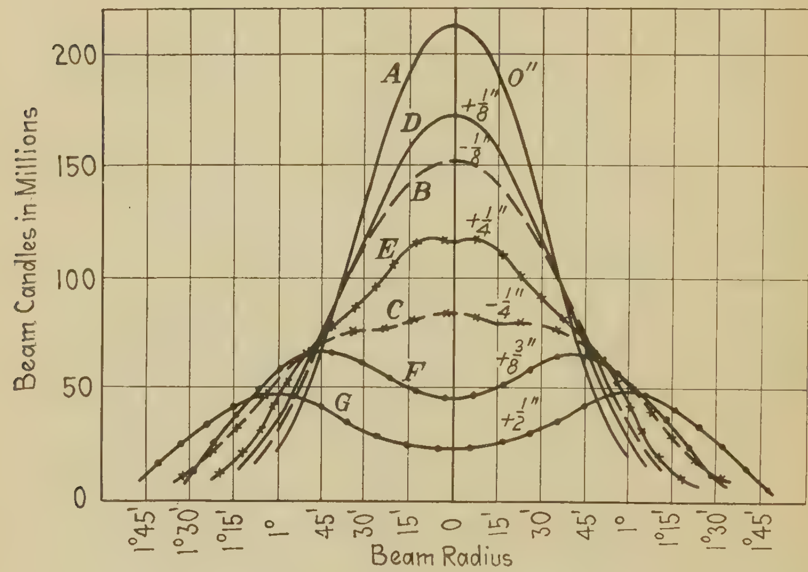


FIG. 274.—The changes that take place in the distribution of light in the beam for positions of the arc closer to the mirror (−) and farther from the mirror (+) than the focal point are illustrated by these curves which apply to a 36-in. mirror. *A*, Crater at focal position; *B*, crater ⅛ in. toward the mirror; *C*, crater ¼ in. toward the mirror; *D*, crater ⅛ in. away from the mirror, *E*, crater ¼ in. away from the mirror; *F*, crater ⅜ in. away from the mirror; *G*, crater ½ in. away from the mirror.

The *observer's position* influences the finding range of a searchlight. The results of tests with airplane targets indicate that the best observing position is in the axis of the trunnion of

the searchlight and from 300 to 1,000 ft. distant. This makes it necessary to have some device whereby the observer can control the searchlight from a distance. This may be accomplished by means of two motors with remote control, one of which is for training in azimuth and the other for elevation.

It is one of the unfortunate peculiarities of a searchlight that the beam itself often forms a most effective concealment for the target. The beam appears as a bright blue-tinted shaft of light and this illuminated space forms a curtain in front of the objects under observation.

Headlights.—Under this subject may be included headlights used on steam and electric locomotives, street cars, and automobiles. The fundamental principle is the same as that of the searchlight. The conditions, however, are not so exacting and the size and the candle power of the units are much smaller.

The most common types employ a parabolic reflector, although some use a spherical mirror and semaphore lens. Some of the more powerful headlights are equipped with a luminous-arc lamp designed for headlight service, while others, and by far the greater number, use the type-C lamp with a concentrated filament.

The *danger zone* ahead of a train or car is equal to the distance required to bring the respective train or car to a stop with emergency breaking. At night it is not sufficient to light only this danger zone but as far beyond as possible in order to increase the factor of safety and give the engine driver or motorman the greatest possible time to bring his conveyance to a stop after sighting an obstruction. Obviously, the higher the speed of the train, the longer it will take to bring it to rest and the more powerful should be the headlight. Also, since the light beam can be seen for a great distance, it serves as a most effectual warning of approach.

In the selection of a headlight that will fulfil all requirements, the contour of the country through which the road passes, the number of curves, and the schedule or speed to be maintained are all factors to be considered.

Street-railway requirements may be divided into three classes: city, suburban, and interurban. The first requires only low-intensity headlights, as the streets are usually well illuminated from other sources. These lamps may be either a standard or focusing filament type of standard railway wattage (23 to 94

watts). The semaphore lens is extensively used, assisted by a small spherical mirror placed back of the lamp. A parabolic reflector used with the regular semaphore lens will give a somewhat wider distribution of light.

Headlights for suburban service on moderate-speed cars in dimly lighted streets of outlying districts should enable the motorman to see objects 300 to 500 ft. away. The reflector used is usually a true paraboloid with clear glass in the door. Lamps of a rating similar to those above may be used.

For interurban service the headlights should have sufficient power to illuminate the track for at least 800 ft. and for higher speeds for 1,200 to 1,500 ft. The reflectors must be accurately made and of the parabolic type. The light source must be concentrated. The headlight should be equipped with a focusing

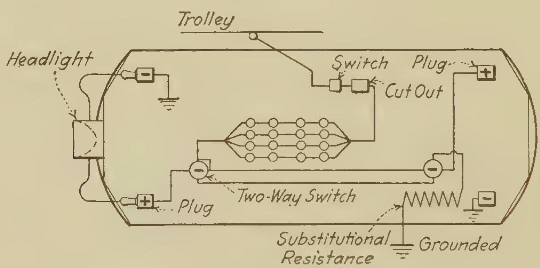


Fig. 275.—Connection diagram showing the lamps inside of the car utilized for resistance.

mechanism which permits adjustment in all three directions. Lamps of sizes up to 500 watts are used for this class of service.

The reflectors may be made of mirrored glass, silver-plated metal, or polished aluminum. The glass reflector is the most efficient, and has greatest initial cost and lowest maintenance. The aluminum reflector ranks lowest in efficiency and first cost and second in maintenance.

The lamps used for best results should have concentrated filaments operating at high efficiency. Unfortunately, the high-current lamps may not yet be used efficiently on 600-volt trolley circuits. On low-voltage train-lighting systems, where storage batteries are feasible, or on alternating-current circuits where a compensator can be used, no obstacles present themselves to the use of these lamps. One method used on street cars is to wire the headlight to burn in series multiple with the lamps in the

car, as shown in Fig. 275. It is obvious that the current rating of the headlight must be equal to or a multiple of the current rating of the inside lamps.

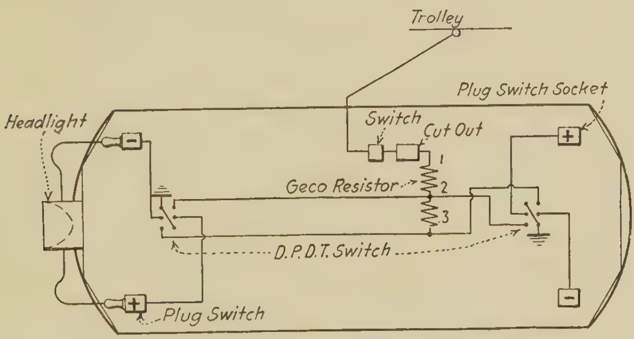


FIG. 276.—Diagram of connections for Geco resistor.

Resistance can be used in series with the headlight as shown in Fig. 276. To compensate for variations in voltage on the line, a special type of resistance unit similar in principle to the Nernst

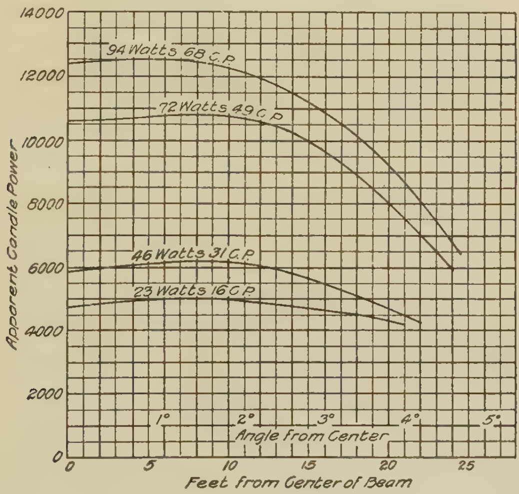


FIG. 277.—Photometric test curves of an incandescent dasher type headlight with 110-volt Mazda B lamp and crystal glass silvered parabolic reflector $8\frac{3}{8}$-in. diameter $1\frac{1}{4}$-in. focus. Readings taken at 300 feet.

lamp ballast has been produced. It consists of a metal resistance, such as iron wire in inert gas in a glass bulb, and operates at the temperature where an increase in current due to higher voltage will produce a decided increase in resistance.

The characteristic curves of some of the different sizes of headlights are shown in the illustrations.

Street cars for city service may have headlights giving a much wider beam, as indicated by the apparent candle-power curves of Fig. 277. These curves show the result when type-B 110-volt lamps are used in a silvered-glass parabolic reflector. Figure 278 indicates the advantage of the more concentrated filament when a 36-watt, 6-volt type-C lamp was used in the same reflector as above, making it satisfactory for suburban service.

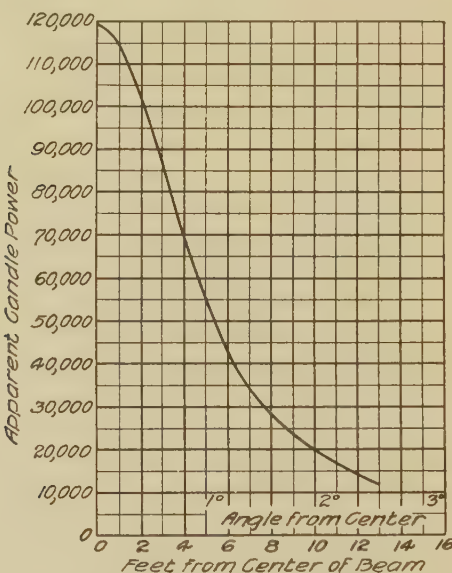


FIG. 278.—Photometric test curve of an incandescent dasher type headlight, with 6-volt, 6-ampere, Mazda C lamp and crystal glass silvered parabolic reflector $8\frac{3}{8}$-in. diameter $1\frac{1}{4}$-in. focus. Readings taken at 300 feet.

The apparent beam candle-power curve shown in Fig. 279 is for a headlight designed for interurban service. It has a shallow parabolic glass mirror with a long focus to accommodate larger lamps. In this case it was equipped with an 80-volt, 4-amp. type-C, focus-type lamp. A 110-volt, 500-watt type-C lamp of the focusing type can also be used.

For *trunk-line service,* such as that of the Chicago, Milwaukee and St. Paul lines, traversing, as they do, states whose statutes require an illuminant of 1,500 unreflected candle power, the

construction of a headlight which would accommodate a 34-volt, 750-watt, focusing type-C lamp was necessary. This headlight was equipped with a ball-and-socket focusing mechanism and had a 20-in. parabolic silvered-metal reflector. It gave approximately 1,150,000 apparent beam candle power as shown in Fig. 280.

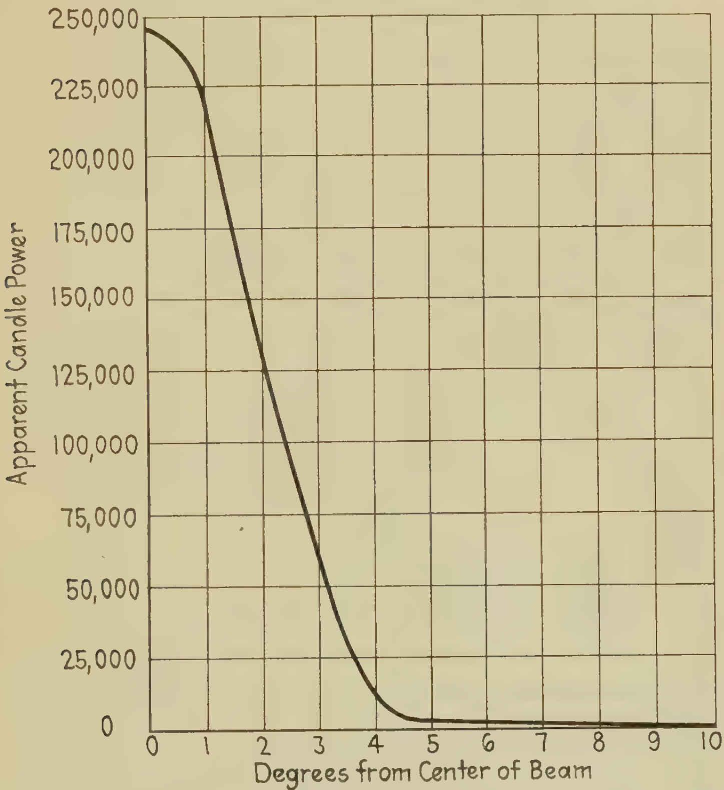


FIG. 279.—Initial distribution of candle-power in a horizontal plane from a 4-ampere, 80-volt, Mazda C headlight lamp. Readings taken at 100 feet; parabolic glass reflector 11-in. diameter; lamp upright.

Figure 281 shows the apparent intensity of a headlight beam considered necessary to see, at different distances, dummies the size of a man dressed in light, medium, and dark clothing. Since a heavy express train, traveling at the rate of 60 miles per hour, can be brought to rest in a distance of 1,300 ft. when equipped with a modern braking system, it would appear from data given

in Figs. 280 and 281 that sufficient intensity could be obtained from incandescent headlights to meet the requirements of the most conscientious of commissioners.

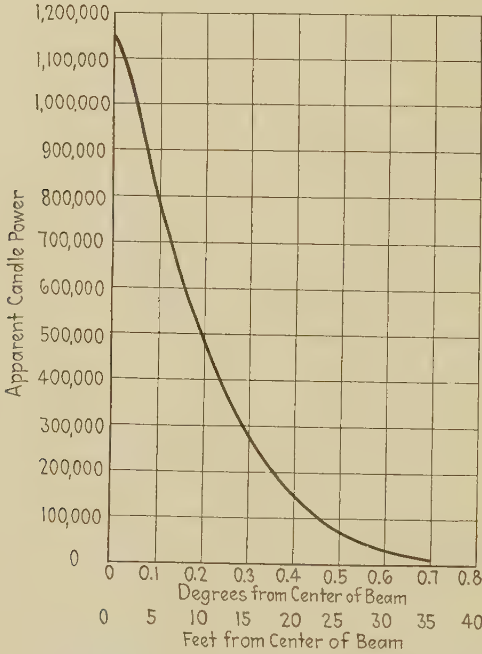


FIG. 280.—Incandescent projector curve of 23.7-ampere Mazda C lamp and polished silver parabola, 20-in. diameter, 2¾-in. focus. Readings at 300 feet.

Automobile Headlights.—The automobile headlight consists almost universally of a parabolic reflector, a 6-volt lamp, and a lens for controlling the distribution of the light. Headlights should be provided which will illuminate the road for several hundred feet in front of the car, and which will not project glaring rays of light into the eyes of approaching drivers or pedestrians. The safety of the public on highways at night depends to such an extent on the above requirements that practically all the states in the Union, as well as the Dominion of Canada, have passed laws regulating and requiring the lighting of automobiles.

Unfortunately, these regulations vary somewhat in different states. In general, this legislation takes the form of limiting the candle power of the lamp that may be used in the headlight, in

requiring headlight beams sufficiently powerful to observe objects certain distances ahead of the car, and in requiring the use of some approved device which controls the distribution of the beam from the headlamps so as to prevent glare.

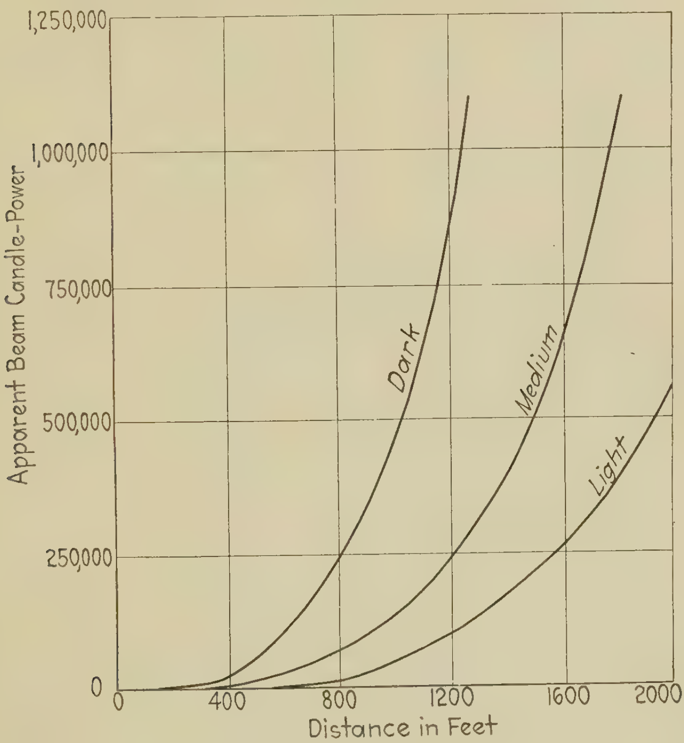


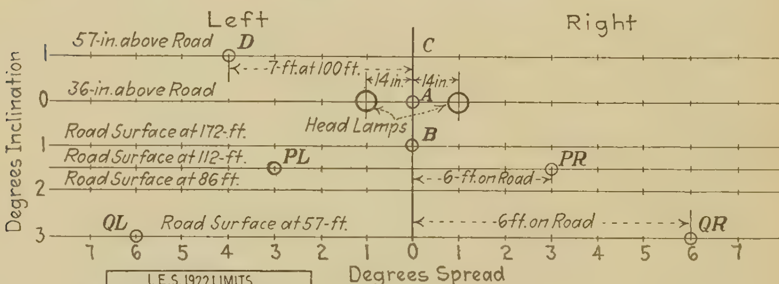
Fig. 281.—Intensity of headlight beam to render light, medium and dark colored dummies visible.

The Illuminating Engineering Society has done a great deal of research work along these lines, and has drawn up specifications for headlight beams. These specifications for the headlight beam are presented in Fig. 282. The centers of the lamps are 36 in. above the road. The center of the beam should be toward *B*, which is at road surface 172 ft. away. This beam should have a minimum of 7,200 c.p. extending 1 deg. to the right and left. Toward the road surface 112 ft. away (*PL* to *PR*) the minimum intensity should be 5,000 candle power for a 6-deg. beam. Above the horizontal and to the left, as at *D* (57 in. above the road and

7 ft. from the axis at 100 ft.), a maximum of 800 c.p. is specified. Other values may be noted in the figure.

In order to comply with these specifications, it is necessary to use high-class headlight lamps and equipment, and to have them carefully adjusted. Undoubtedly, the greatest difficulty from glaring lights and poor road illumination is due to the improper adjustment of the equipment. The average car owner does not know how to adjust his headlamps, and most of those who know seldom do it.

Guides are issued by the lamp manufacturers, which tell exactly what lamps to use for every make of car on the market.



I. E. S. 1922 LIMITS	
A 1800 cp. Min.	6000 Max.
B 1° Right and Left	7200 Min.
C 800 cp. Min.	2400 Max.
D	800 Max.
PL to PR	5000 Min.
QL to QR	2000 Min.

FIG. 282.—Specifications for motor vehicle headlight beams as drafted by the illumination engineering society.

Suffice it to say here that it is of the utmost importance to use only lamps which are made with great accuracy and high filament concentration, such as the 21-c.-p., gas-filled, type-C lamp.

Some cars have special lamps—dome lamps, etc.—but the tendency is strongly toward the use of standard lamps throughout, and in but two sizes, 21 and 2 c.p. The cars formerly using 12- to 16-volt lighting systems are steadily coming over to 6- to 8-volt systems.

The best lamps must be focused very carefully. The following focusing instructions have been issued by the Headlight Committee of the Illuminating Engineering Society.

Adjustment of Tilt.—Place the car fully loaded on a level surface, as, for instance, the floor of the garage. Measure the height of the center of the headlamps from the floor, and cut off two

sticks to a length equal to this height. Stand one of the sticks, near the front end of the car, and the other near the rear. Arrange a board so that it will stand on end, and set this up as a target at a distance of 25 ft. ahead of the lamps, so that the light of one headlamp or of both shines upon it. Remove the front glass from the lamp, or use only the plain glass, and operate the focusing adjustment so that the light forms a small patch on the target. Sight over the top of the two vertical markers on to the target and place a line at the point thus found. This will give the horizontal line. If the height of the center of the beam comes at the same height as this mark, the beam is horizontal. If the device which is to be used is one requiring a tilted beam, put another mark on the target at the requisite distance below the first mark. For instance, if a tilt of 2 ft. in 100 is required, the target being 25 ft. ahead of the lamps, the mark should be placed 6 in. below the horizontal mark. The headlamp is then tilted until the center of the beam comes at this lower mark with the car fully loaded. By shifting the target, the other lamp can be similarly adjusted. The actual tilting of the headlamps is a mechanical adjustment, which in some makes of cars is very simple, and in others requires some mechanical skill. See that the beams of both lamps point straight ahead. The horizontal distance between the centers of the beams should equal the distance between the centers of the headlamps.

For focusing, nearly all headlamps are provided with an arrangement whereby the position of the bulb may be changed with respect to the focal point of the parabolic mirror. Some devices require one adjustment and some another. A common adjustment is to have the center of the filament at the focus of the reflector. The rays are then generally parallel and the light spot of minimum diameter.

If the lamp is placed forward or backward of the focal point, the rays will spread and the light spot will be larger with a dark center. By blowing a cloud of smoke into the beam, which of these operations is taking place may be told from the shape of the beam in front of the lamp. Moving the light source up from the axis throws the beam down, and *vice versa*. Moving the light to the right throws the beam to the left, and *vice versa*.

When the right tilt and focus adjustment have been secured the controlling device which it is proposed to use is affixed to the headlamps, care being taken to see that it is placed exactly in

accordance with the manufacturer's instructions, which should accompany the device. The beam is then once more observed on the target to see whether the upper half of the beam is properly cut off and the light deflected toward the road (Fig. 283). In many devices, this cut-off is secured with the bulb at the reflector focus. In some, however (those which obstruct the light from the upper part of the headlamp), the bulb must be brought back toward the reflector in order to secure the cut-off. With still others (those which obstruct the light from the lower half of the reflector) the bulb must be pushed forward ahead of the focal point. In any case, a little experimenting will show

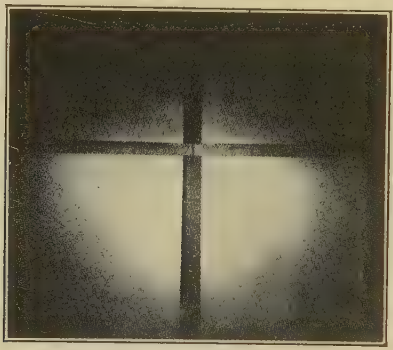


FIG. 283.—Beam deflected toward the road by auxiliary device.

what adjustment is necessary in order to secure the sharpest possible cut-off of the upper half of the beam.

There are many devices on the market for reducing the glare from headlights. The greater number of these are diffusing lenses which reduce the intensity of the beam to a small fraction of its former value and increase hundreds of times the size of the solid angle in which glare is experienced. While an accurately made parabolic headlighting unit may produce blinding glare in the angle of the beam, its field of action is limited within a small angle. The approaching driver may face the beam at a considerable distance, but is likely to escape it when nearer the approaching car. Figure 284 illustrates the distribution of light from three typical classes of equipment; an unmodified parabola with covers of clear glass, partly frosted "lens," and all-frosted diffusing glass.

The solution of the problem is in the direction indicated by the Illuminating Engineering Society's specifications, which require

a rather intense beam accurately directed as shown in Fig. 283. Prismatic lenses are used for this purpose, as indicated in Fig.

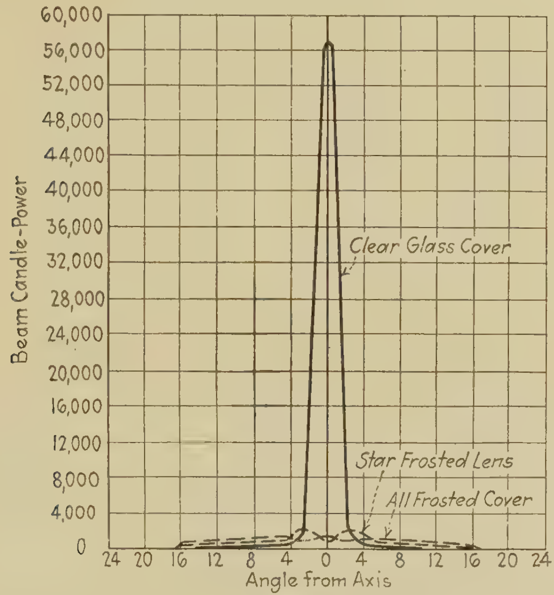


FIG. 284.—Beam candle-power of parabolic automobile projector with 6–8 volt 3.0-ampere Mazda C lamp. (From *Illuminating Engineering Practice.*)

285. The rays are refracted toward the roadway. Obviously, the same effect could be obtained by tilting the lamp, which would

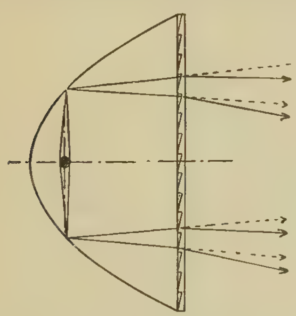


FIG. 285.—Action of light rays originating from a source located at the focal point of a parabolic reflector equipped with a prismatic glass cover.

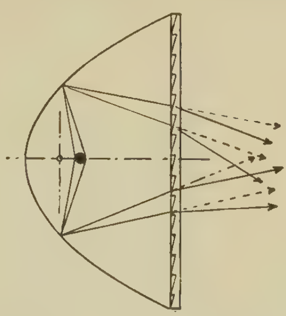


FIG. 286.—Action of light rays originating from a source ahead of the focal point of a parabolic reflector equipped with a prismatic cover glass.

produce satisfactory results with an accurately made parabolic reflector.

In another class use is made of compound curvatures in the reflector. There is the offset parabola where the upper half has its focal point back of that of the lower half. Also one having the upper half tilted downward. Still another is a combination consisting of a parabolic lower part and an ellipsoidal upper part.

The beam from a pair of good headlights equipped with 21-c.-p. lamps of good design and approved glare-reducing lenses

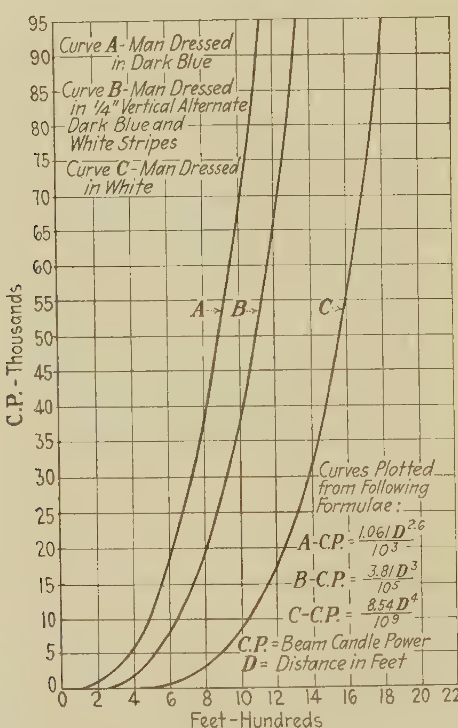


FIG. 287.—Pick-up distance for various conditions.

will average about 20,000 c.p., varying with the type of lenses used.

The intensity of the beam necessary to detect objects at various distances involves many factors, such, for example, as the contrast between the object and its background, the relative rest or motion of the object and observer, the amount of extraneous light entering the observer's eye from surrounding light sources or other headlights, etc. The curves in Fig. 287 show the

approximate beam candle powers and pick-up distances for light-, medium-, and dark-colored objects seen against a dark background. Figure 288 shows the breaking distance required

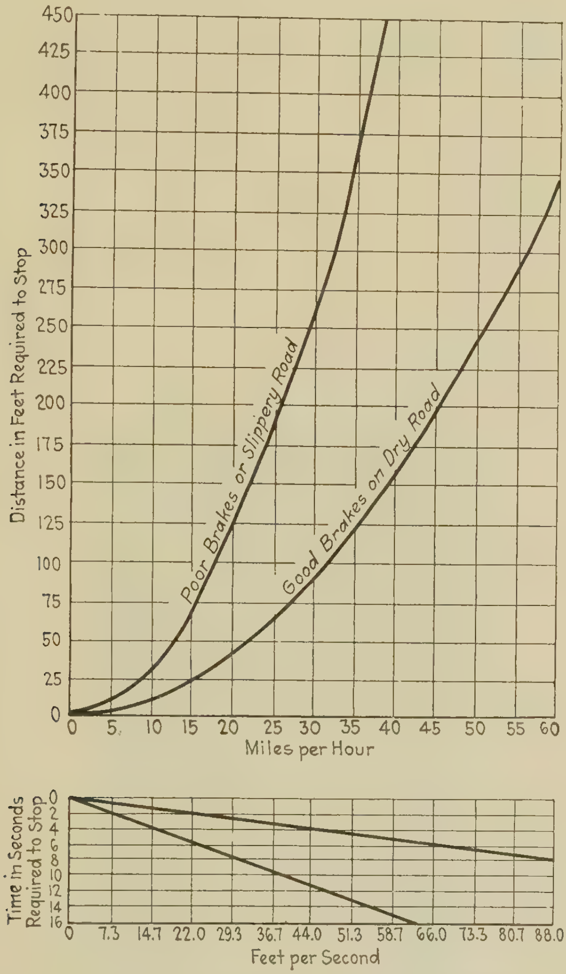


FIG. 288.—Braking distance for various conditions.

to stop automobiles traveling at different speeds on wet and dry roads.[1]

Floodlighting Projectors.—Floodlighting is a comparatively new type of illumination. It is successfully used for facilitating

[1] *Ohio Motorist*, February, 1922, p. 24.

night activities in connection with manufacturing plants, freight terminals, railroad yards, piers, shipyards, docks, race tracks,

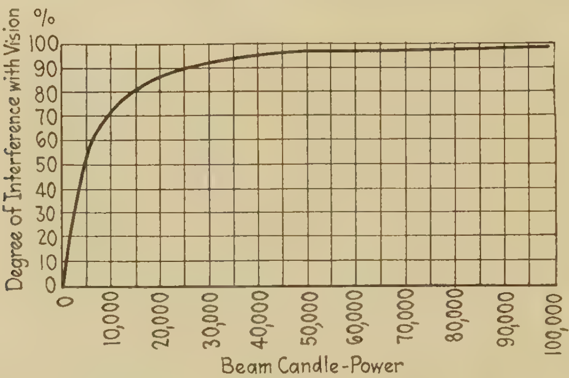


FIG. 289.—Nature of relation between beam candle-power and visibility of objects viewed against beam where the background is totally dark.

FIG. 290.—Statue of Liberty floodlighted.

athletic fields, and rifle ranges. It is also used for utilitarian or decorative effects in connection with the illumination of clock

towers, public squares, building fronts, flags, statues, theater fronts, outside theatricals, fountains, billboards, signs, advertising banners, etc.

The type of floodlight to use depends on local conditions. When studying local conditions, three factors must be carefully considered before specific conclusions can be deduced as to the type of unit best suited to the purpose:

1. The distance from the surface to be illuminated to the place where the projector is to be located.

2. Whether the surface to be lighted is located along a "white-way," residential section, park, or in a place where there is no stray light.

3. The color of the surface or object to be lighted.

If a small area is to be illuminated by a floodlight, obviously the type having a narrow beam of light should be chosen; for a large area the unit should have a wide beam. The beam spread of standard floodlighting units varies from 8 to about 50 deg. The area covered by one unit depends not only on the spread of the beam but upon the distance from the unit.

The two latter factors are important in determining the foot-candle intensity and the number of units required for each installation. Some of the intensities for floodlighting are given in Table 46.

TABLE 46

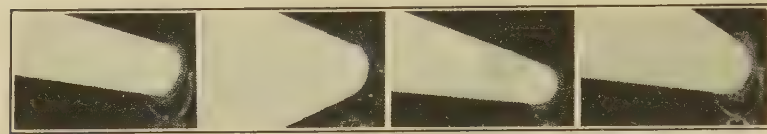
Intensities for Floodlighting

	Character of surroundings		
	White-way, foot-candles	Residences, foot-candles	Parks, foot-candles
Dark-colored buildings.........	20	15	10
Medium-colored buildings......	15	10	5
Light-colored buildings.........	10	5	3

The angle between the axis of beam and the surface lighted must not be less than 70 deg.

The data furnished in Fig. 291 and Table 46 will facilitate the solving of floodlighting problems. In the upper part of

Fig. 291 are shown the beam spreads of four forms of projectors. Data shown in the middle of the figure are for low-intensity floodlighting and those in the lower part of the figure refer to high-intensity service.



Form L-1 400 watt floodlighting lamp.	Form L-3 400 watt floodlighting lamp.	Form L-11 200 watt floodlighting lamp.	Form L-12 1,000 watt Mazda multiple lamp.

Distance from Projector-Feet	Diameters, Areas and Intensities for One Unit Only											
	8° Beam			50° Beam			16° Beam			30° Beam		
	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles
25	3.5	9.6	148.000	22.3	389	6.750	7	38.5	33.800	13.4	141	67.100
50	7.0	38.5	37.000	44.6	1556	1.680	14	154.0	8.430	26.8	564	16.800
100	14.0	154.0	9.250	93.0	6793	0.385	28	616.0	2.110	54.0	2290	4.140
200	28.0	616.0	2.310	186.0	27172	0.096	56	2463.0	0.527	108.0	9161	1.030
400	56.0	2463.0	0.580	372.0	108687	0.024	112	9852.0	0.132	216.0	36644	0.258
600	84.0	5542.0	0.257	558.0	244545	0.011	168	22167.0	0.059	324.0	82448	0.115
800	112.0	9852.0	0.145	744.0	434746	0.006	224	39408.0	0.033	432.0	146574	0.065
1000	140.0	15394.0	0.093	930.0	679292	0.004	280	61575.0	0.021	540.0	229022	0.041

Working distance 155 to 500 ft.	Working distance 25 to 75 ft.	Working distance 80 to 255 ft.	Working distance 40 to 130 ft.

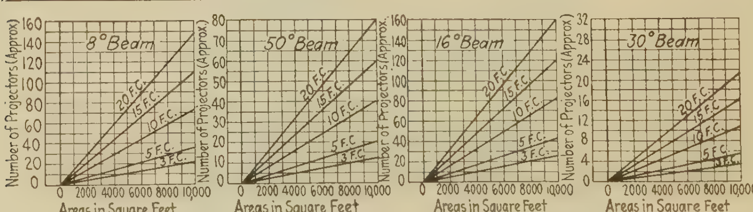


FIG. 291.—General data on floodlighting projectors for low and high-intensity illumination. Working distances are given for convenience in selecting the proper floodlighting projector. Local conditions may necessitate a change in some cases.

The method of applying these data is as follows: Consider the problem of floodlighting a building surface of 6,000 sq. ft. located in a white-way district. The local conditions are such that the units must be installed 130 ft. away. The color of the building surface is dark.

Reference to Fig. 291 shows that for a working distance of 130 ft. the L-12 unit may be used. From the table of intensities it

is noted that the intensity required is 20 foot-candles. Referring now to the curves for the L-12 unit, it will be seen that, for an area of 6,000 sq. ft. and an intensity of 20 foot-candles, thirteen L-12 units are required for the installation.

For low-intensity floodlighting, data are given for distances from 25 to 1,000 ft. from the projector indicating the diameters,

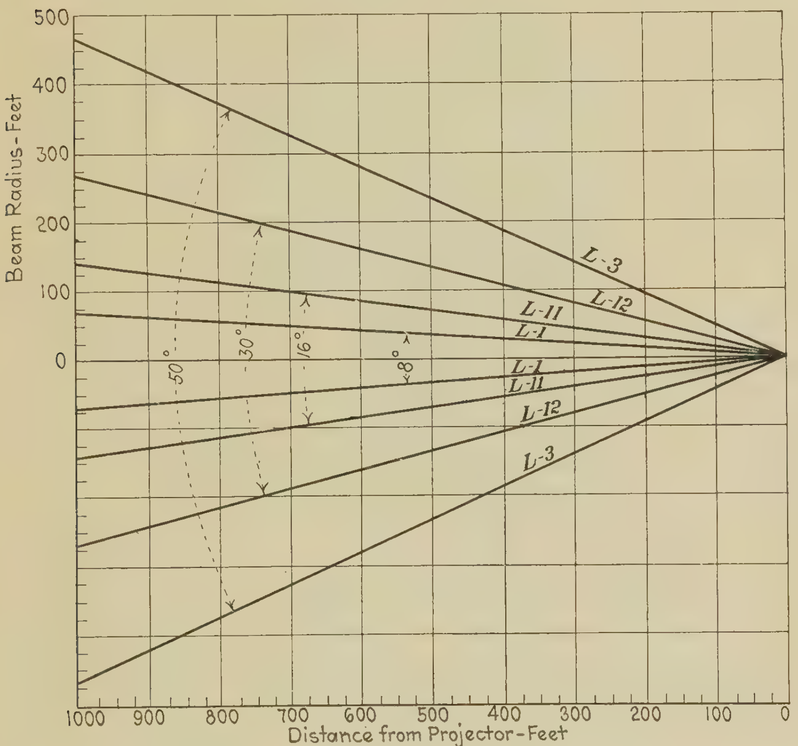


FIG. 292.—Beam angle for different projectors.

areas, and intensities of the beams of each form of unit. Consider an area of approximately 15,000 sq. ft. to be illuminated and the units to be installed 1,000 ft. away. The surroundings are such that no other source of light is present. From the data for the L-1 unit it is noted that 1,000 ft. away the area of the beam is 15,394 and the intensity 0.093 foot-candle. To increase the intensity, additional units should be installed. Figure 292 shows graphically the relation of the radius of the beam to the

distance from the source. This makes it possible to obtain intermediate values not given in Fig. 292.

The construction of a floodlight projector is indicated by Fig. 293. The reflector may be of spun aluminum highly polished or

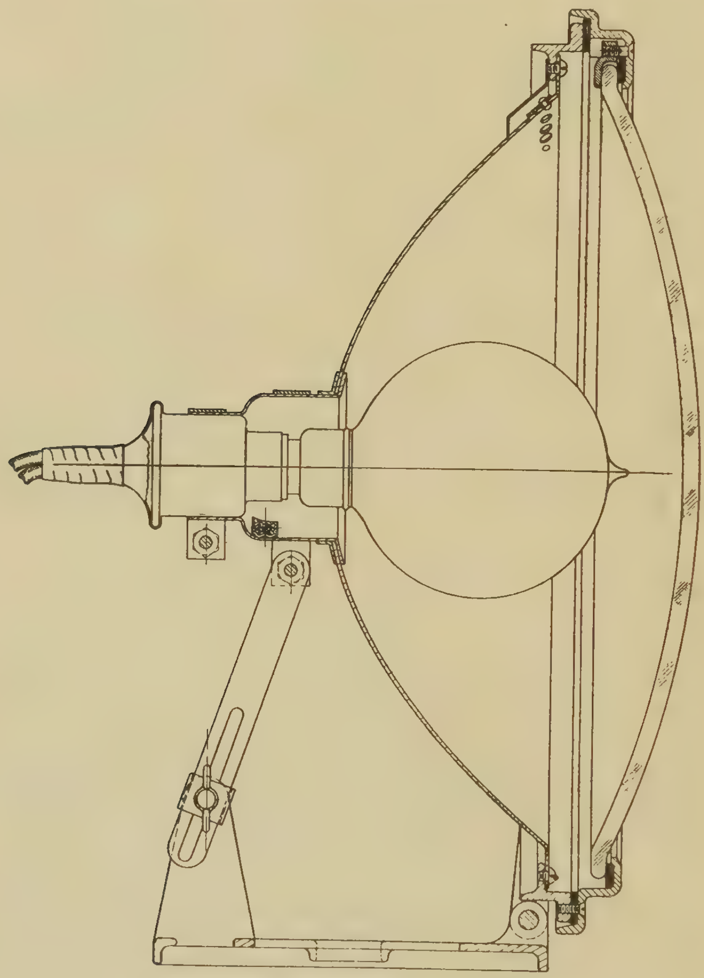


FIG. 293.—Showing the construction of a floodlight projector.

it may consist of sectional copper-backed glass mirrors assembled in a sheet-metal support. The reflector and the lamp are mounted in a weatherproof iron casing having in front a convex pane of heat-resisting glass. The focusing mechanism is located on the back of the casing.

Glass lenses are constructed to redirect the light from a projector, so that beams of various shapes and spreads can be obtained. Some prismatic-type lenses produce a rectangular-shaped beam. Such lenses placed across a 10-deg. beam will

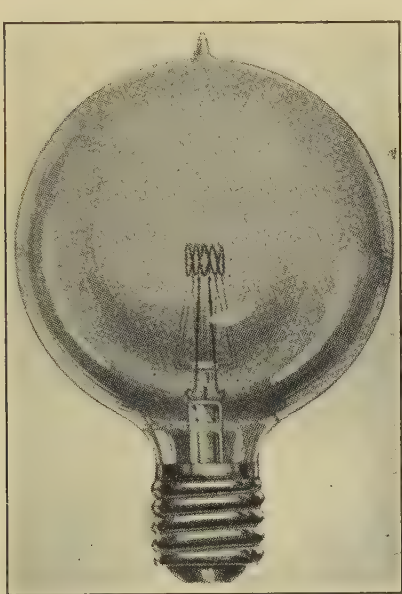


FIG. 294.—Mazda C floodlighting lamp 500 watt size.

spread the beam to 50 to 90 deg. in a horizontal plane, the divergence remaining 10 deg. in the vertical plane.

The lamps used in floodlights have concentrated filaments and round bulbs, as shown in Fig. 294.

APPENDIX A

PROBLEMS

1. Find the frequency of vibration of light in the region of the spectrum at which highest visible sensibility occurs.

2. Assuming the spherical reduction factor of the Hefner lamp to be 0.8, what should be its rating in mean spherical candle power?

3. An illumination survey showed an average illumination intensity of 4.5 foot-candles with 105 volts on the installation. What should be the illumination with normal voltage (110 volts) on the lamps?

4. A standardized 20-c.-p. tungsten lamp was used to photometer another tungsten lamp. The results indicated 35 c.p. for the latter. Upon calibrating the voltmeters, it was found that the standard lamp was operating 1 per cent more than normal voltage and the test lamp 2 per cent under normal voltage. What should be the correct candlepower of the test lamp?

5. A 20-c.-p. lamp is placed at the zero end of a photometer bar 300 cm. long. A 50-c.-p. lamp was placed at the other end (300 cm. from the first lamp). What should be the distance from the photometer screen to the 20-c.-p. lamp?

6. The readings on a standard photometer were 100 cm. on the side of the 20-c.-p. standard lamp and 200 cm. between the photometer head and the test lamp. A sectored disk with one-third of its surface removed revolved in line with the test lamp. What is the candle power of the test lamp?

7. Absorbing screens having a transmission coefficient of 0.1 and 0.01 are used in the Sharp-Millar photometer. The apparatus was calibrated to read foot-candles with the screens not in use. If the position of the screens is not known and the setting indicates 20 foot-candles, what may be the value of the illumination?

8. On a piece of tracing cloth or translucent paper reproduce Fig. 75 and determine the mean spherical and mean lower hemispherical candle power and lumens for Fig. 70*c* or some other assigned by the instructor.

9. On a piece of tracing cloth or translucent paper reproduce Fig. 78 and determine the mean spherical and mean lower hemispherical candlepower and lumens for Fig. 70*d* or some other assigned by the instructor.

10. Check the results obtained in the two preceding problems by marking off the midzone distances from the vertical on the edge of a sheet of paper as explained in the text under Wohlauer's method.

11. How many lumens are emitted by the lamp referred to in Fig. 218, curve A, in the zone extending from 60 to 90 deg. from the vertical?

12. A 250-c.-p. street lamp is on the same level with a second-story window. The light passes through the glass to a silvered glass mirror 100 ft. from the lamp. It is reflected specularly to a wall 10 ft. away. What normal-incident illumination would be expected on the wall?

13. A spherical globe 18 in. in diameter and of good diffusing quality has an intensity of 4 candles per square inch. If the transmission coefficient of the globe is 0.80 and the spherical reduction factor of the type-C lamp within is 0.85, what will be the mean horizontal candle power of the lamp?

14. A customer using 100-watt tungsten lamps found the average voltage to be only 90 per cent normal. Upon complaint the company raised the voltage to 105 per cent normal. The customer put 75-watt lamps in place of the 100-watt lamps. How many lumens per lamp and lumens per watt were obtained in each case? What relative electric-light bill resulted?

15. A living room 16 by 20 ft. having a light ceiling and medium-colored walls is lighted by a 200-watt type-C lamp in a mirrored indirect luminaire. What should be the average foot-candle intensity of illumination?

16. Specify the location and size of lamps for lighting a store 40 ft. wide and 100 ft. deep, having fairly light ceilings and medium walls. The one-piece opal unit with a flattened reflecting top was adopted for the installation. Assume an illumination of 8 foot-candles. Refer to the curves in latter part of Chap. IX.

17. Choose the lighting system and locate the units for lighting a general office 60 by 100 ft. with a ceiling 16 ft. above the floor. The ceiling is white. The walls consist of 50 per cent glass, the remainder being fairly dark. Determine the size of type-C lamps to give the necessary illumination for accurate office work.

18. The indoor field of the University of Maine armory-gymnasium is 304 by 170 ft. The roof along the center is 67 ft. above the ground. Along the sides it is 30 ft. high. It is of the arch style. Design a lighting installation that will meet the requirements for baseball practice.

19. A street is lighted by lamps giving candle power and distribution indicated by curve *a*, Fig. 228. If these lamps are placed 100 ft. apart and on opposite sides of a street 40 ft. wide, what will be the horizontal illumination

(*a*) In center of street between opposite lamps?
(*b*) In center of street equidistant from four lamps?
(*c*) Halfway between lamps along the curb?
(*d*) One-fourth the way between lamps along the curb?

20. If 60 per cent of the light from a lamp of 500 m.s.c.p. be gathered into a 15-deg. floodlight beam, what should be the intensity of the beam and the incident illumination on a building 200 ft. distant?

21. If 40 per cent of the light from a lamp emitting 500 m.s.c.p. be concentrated into a 2-deg. searchlight beam, what should be the intensity of the beam and the incident illumination on an object ¼ mile away?

APPENDIX B

REFERENCES

Transactions of the Illuminating Engineering Society, vols. 1 to 20.

"Lectures on Illuminating Engineering," Johns Hopkins University and the Illuminating Engineering Society, The University Press, 1911.

"Illuminating Engineering Practice," University of Pennsylvania and the Illuminating Engineering Society, McGraw-Hill Book Company, Inc., 1916.

BIBLIOGRAPHY

"The Visibility of Radiant Energy," by K. S. Gibson and E. P. Tyndall, *Trans. Illum. Eng. Soc.*, vol. 19, p. 176.

"Experiments on the Eye with Different Illuminants and Intensities," by C. E. Ferree and G. Rand, *Trans. Illum. Eng. Soc.*, vol. 13, p. 50; vol. 14, p. 107, vol. 15, p. 769.

"Studies on the Effect of Composition of Light on Important Ocular Functions," by C. E. Ferree and G. Rand, *Trans. Illum. Eng. Soc.*, vol. 17, p. 69; vol. 19, p. 424.

"Photometry as Related to Illuminating Engineering," by W. F. Little, *Trans. Illum. Eng. Soc.*, vol. 19, p. 497.

"Flicker Photometry," by C. E. Ferree and G. Rand, *Trans. Illum. Eng. Soc.*, vol. 18, pp. 151, 174.

"Commercial Photometry" (and bibliography), by A. L. Powell and J. A. Summers, *Gen. Elec. Rev.*, vol. 23, p. 954; vol. 24, p. 50.

"Finite-surface Light Sources," by Bassett Jones, Jr., *Trans. Illum. Eng. Soc.*, vol. 4, p. 216; vol. 5, p. 281; vol. 6, p. 263.

"Graphical Solution of Problems Involving Plane-surface Lighting Sources," by A. S. McAllister, *Elec. World*, vol. 56, p. 1356.

"Design of Illuminating Installations Using Luminous Tubes," by M. D. Cooper, *Elec. World*, vol. 54, p. 718.

"Coefficient of Utilization," by W. Harrison and E. A. Anderson, *Trans. Illum. Eng. Soc.*, vol. 15, p. 97.

"Luminescence as a Factor in Artificial Lighting," by E. L. Nichols, *Trans. Illum. Eng. Soc.*, vol. 16, p. 331.

"Incandescent-lamp Temperatures as Related to Modern Practice," by C. L. Dows and W. C. Brown, *Trans. Illum. Eng. Soc.*, vol. 16, p. 284.

"Testing of Incandescent Lamps at the Bureau of Standards," *Bur. Stand., Bull.* 265.

"Relative Performance of Tungsten-filament Lamps under Test upon Alternating- and Direct-current Circuits," by J. W. Leib, *Trans. Illum. Eng. Soc.*, vol. 18, p. 5.

"Wrought Tungsten," by W. D. Coolidge, *Trans. Amer. Inst. Elec. Eng.*, vol. 29, p. 961.
"The Blackening of Tungsten Lamps and Method of Preventing It," by I. Langmuir, *Trans. Amer. Inst. Elec. Eng.*, vol. 32, p. 1913.
"Nitrogen-filled Lamps," by I. Langmuir and J. A. Orange, *Trans. Amer. Inst. Elec. Eng.*, vol. 32, p. 1935.
"Some Fundamental Characteristics of Mercury-vapor Apparatus," by P. H. Thomas, *Trans. Amer. Inst. Elec. Eng.*, vol. 25, p. 531.
"Gaseous Conduction Light from Low-voltage Circuits," by D. McFarlan Moore, *Trans. Amer. Inst. Elec. Eng.*, vol. 39, p. 2021.
"Light and Gaseous Conductors within Glass Tubes," by D. McFarlan Moore, *Trans. Amer. Inst. Elec. Eng.*, vol. 26, p. 605.
"A Low-voltage, Self-starting, Neon-tungsten Arc-incandescent Lamp," by D. McFarlan Moore, *Trans. Illum. Eng. Soc.*, vol. 16, p. 346.
"Neon-tube Lighting," by Georges Claude, *Trans. Illum. Eng. Soc.*, vol. 8, p. 371.
"Maintenance of Indirect Lighting Equipment," by J. L. Stair, *Trans. Illum. Eng. Soc.*, vol. 15, p. 292.
"Depreciation of Lighting Equipment Due to Dust and Dirt," by E. A. Anderson and J. M. Ketch, *Trans. Illum. Eng. Soc.*, vol. 19, p. 55.
"Maintenance of Interior Lighting Systems," by A. L. Powell, *Elec. Rev.*, vol. 76, p. 263.
"Effect of Color of Walls and Ceilings on Resultant Illumination" (and bibliography), by A. L. Powell, *Gen. Elec. Rev.*, vol. 23, p. 209.
"Illumination without the Use of Pendent Ceiling Fixtures," by A. D. Curtis and J. L. Stair, *Trans. Illum. Eng. Soc.*, vol. 15, p. 61.
"Home Lighting," by A. L. Powell and R. E. Harrington, *Trans. Illum. Eng. Soc.*, vol. 14, p. 394.
"Code of Lighting School Buildings," *Trans. Illum. Eng. Soc.*, vol. 19, p. 375.
"Symposium on Office Lighting," *Trans. Illum. Eng. Soc.*, vol. 19, p. 531.
"Lighting of Public Buildings" (and bibliography), by A. L. Powell and E. Parker, *Trans. Illum. Eng. Soc.*, vol. 16, p. 533.
"Departures from Usual Lighting Practice in Public Spaces and Offices," by A. D. Curtis and J. L. Stair, *Trans. Illum. Eng. Soc.*, vol. 16, p. 551.
"The Lighting of the Milwaukee Art Institute," by H. W. Bogner and A. J. Sweet, *Trans. Illum. Eng. Soc.*, vol. 17, p. 434.
"Hospital Operating-room Lighting," by Norman Macbeth, *Trans. Illum. Eng. Soc.*, vol. 18, p. 846.
"Lighting for Public Eating Places," by J. L. Stair, *Trans. Illum. Eng. Soc.*, vol. 17, p. 621.
"Illumination of Small Stores," by A. L. Powell, *Trans. Illum. Eng. Soc.*, vol. 17, p. 289.
"Applications of Color to Lighting," by A. D. Curtis, *Trans. Illum. Eng. Soc.*, vol. 15, p. 678.
"Colored Lighting" (and bibliography), by M. Luckiesh and A. H. Taylor, *Trans. Illum. Eng. Soc.*, vol. 19, p. 135.
"Factors in Electric-sign Design," by C. A. Atherton, *Trans. Illum. Eng. Soc.*, vol. 16, p. 397.
"Better Signs," C. A. Atherton, *Trans. Illum. Eng. Soc.*, vol. 17, p. 211.

"Daylight Intensity at Window Opening," H. H. Kimball, *Trans. Illum. Eng. Soc.*, vol. 19, p. 217.

"Principles Governing the Proper Utilization of the Light of Day," by W. S. Brown, *Trans. Illum. Eng. Soc.*, vol. 19, p. 269.

"Code of Lighting—Factories, Mills, and Other Work Places," *Trans. Illum. Eng. Soc.*, vol. 16, p. 362.

"Lighting in the Food Industries," by W. H. Rademacher, *Trans. Illum. Eng. Soc.*, vol. 17, p. 548.

"Cotton Mill Lighting," by J. M. Ketch, *Trans. Illum. Eng. Soc.*, vol. 17, p. 577.

"Lighting in the Clothing Industry," by A. B. Oday and R. W. Peden, *Trans. Illum. Eng. Soc.*, vol. 16, p. 606.

"Lighting of Shoe Factories," by A. L. Powell and J. H. Kurlander, *Trans. Illum. Eng. Soc.*, vol. 15, p. 603.

"Artificial Illumination in the Iron and Steel Industry," by W. H. Rademacher, *Trans. Illum. Eng. Soc.*, vol. 18, p. 824.

"Relation of Illumination to Production," by D. P. Hess and Ward Harrison, *Trans. Illum. Eng. Soc.*, vol. 18, p. 787.

"Effect of Light on Plant Growth," *Trans. Illum. Eng. Soc.*, vol. 19, pp. 981, 995, 998, 1000, 1011.

"Lighting Outdoor Tennis Courts," by A. L. Powell and A. B. O'Day, *Elec. World*, vol. 63, p. 1398.

"Night Golf at Briarcliff Convention," by W. T. Dempsey, *Trans. Illum. Eng. Soc.*, vol. 19, p. 882.

"Some Notes on Street Lighting," by P. S. Millar, *Jour. Amer. Inst. Elec. Eng.*, vol. 43, p. 495.

"The Effective Illumination of Streets," by P. S. Millar, *Trans. Amer. Inst. Elec. Eng.*, vol. 34, p. 1429.

"An Unrecognized Aspect of Street Illumination," by P. S. Millar, *Trans. Illum. Eng. Soc.*, vol. 5, p. 546.

"An Analysis of Illumination Requirements in Street Lighting," by A. J. Sweet, *Jour. Franklin Inst.*, 1910.

"Some Neglected Considerations Pertaining to Street Lighting," by P. S. Millar, *Trans. Illum. Eng. Soc.*, vol. 5, p. 653.

"Tests of Street Illumination," by P. S. Millar, *Trans. Illum. Eng. Soc.*, vol. 11, p. 479.

"Street-lighting Glassware," by S. L. E. Rose, *Gen. Elec. Rev.*, vol. 24, p. 740.

"Architectural Aspects of Street Lighting," by J. W. Gosling, *Gen. Elec. Rev.*, vol. 24, p. 701.

"Eleven Solutions of a Street-lighting Problem," *Trans. Illum. Eng. Soc.*, vol. 18, p. 885.

"Street Lighting with Modern Electric Illuminants," by S. L. E. Rose and H. E. Butler, *Gen. Elec. Rev.*, vol. 20, p. 945.

"Intensive or Super White-way Lighting," by W. D'A. Ryan, *Gen. Elec. Rev.*, vol. 24, p. 692.

"Street Lighting with Low-mounted Units," by C. A. B. Halvorson and A. B. O'Day, *Trans. Illum. Eng. Soc.*, vol. 15, p. 153.

"Study of Lighting for Hudson River Vehicular Tunnel," by R. E. Shackelford and D. W. Atwater, *Trans. Illum. Eng. Soc.*, vol. 19, p. 638.

"Highway Lighting," H. E. Butler, *Gen. Elec. Rev.*, vol. 25, p. 465.
"Military Searchlights," by Chester Lichtenberg, *Trans. Illum. Eng. Soc.*, vol. 15, p. 1.
"Desired Road Illumination from Automobile Headlights," by H. H. Magdsick, and R. N. Falge, *Trans. Illum. Eng. Soc.*, vol. 16, p. 480.
"Incandescent Headlights for Street Railway and Locomotive Service," by P. S. Bailey, *Gen. Elec. Rev.*, vol. 19, p. 638.
"Color Floodlighting of Buildings," by A. N. Gerber and E. D. Tillson, *Trans. Illum. Eng. Soc.*, vol. 19, p. 518.
"Lighthouses and Light Vessels," S. G. Hibben, *Trans. Illum. Eng. Soc.*, vol. 18, p. 241.
"Motion-picture Lighting," W. B. Ihnen and D. W. Atwater, *Trans. Illum. Eng. Soc.*, vol. 19, p. 902.

INDEX

73-11